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BIBLIOGRAPHY OF ICE PROPERTIES AND FORECASTING RELATED TO TRANS--ETC(U)
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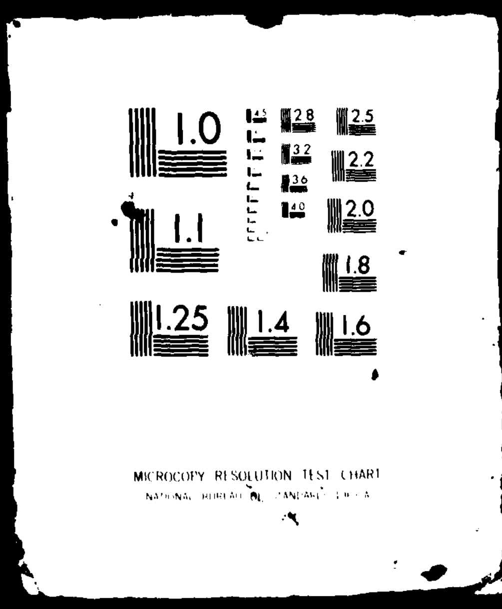

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16. Abstract

This bibliography is intended as a tool for those performing research in ice properties related to ships; particularly icebreaker, operations. The areas covered are the properties of lake, sea and river ice as they relate to mechanical behavior, remote sensing, and ice motions. Other topics included are: ice climatology, pressure ridges, shipping routes, vehicles and vessels, scientific studies by the Arctic Ice Dynamics Joint Experiment (AIDJEX) and other bibliographies.

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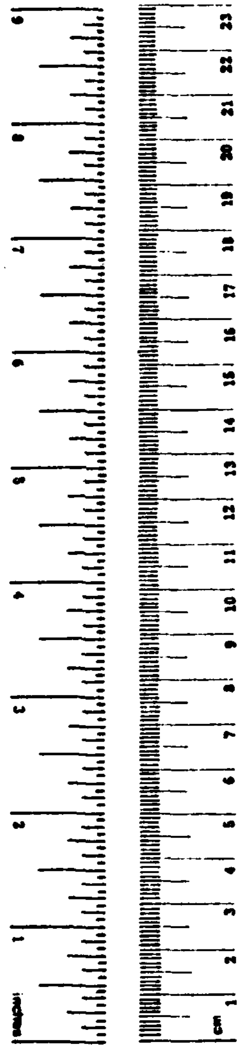
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

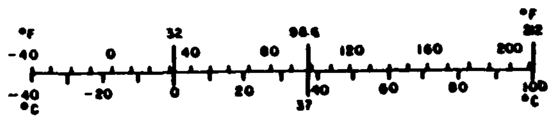
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | **AREA** | | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | **MASS (weight)** | | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | **VOLUME** | | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | **TEMPERATURE (exact)** | | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | **AREA** | | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | **MASS (weight)** | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | **VOLUME** | | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | **TEMPERATURE (exact)** | | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



# Bibliography of Ice Properties and Forecasting Related to Transportation in Ice-Covered Waters

# Bibliography of Ice Properties and Forecasting Related to Transportation in Ice Covered Waters
# Contents

# INTRODUCTION

This bibliography was compiled as the initial effort in the Coast Guard Research and Development Center's Ice Properties Research Project. As such, it was intended to be both an educational process for the investigator and a useful tool for other researchers. The covered field is relatively broad, however emphasis has been placed on areas that may be relevant to research related to Coast Guard missions.

With the exception of sections 14 and 15, the citations are grouped by subject. Section 14 is a bibliography of bibliographies on sea ice and was compiled by N. Dumont, the librarian at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Section 15 comprises three groups of excerpts from a bibliography prepared by N. Dumont for the Ice Panel of the *15th International Towing Tank Conference*. The three groups are Resistance, Strength Properties, and Navigation In Ice.

National Technical Information Service (NTIS) and CRREL reference numbers appear throughout the bibliography. The NTIS numbers refer to the order numbers that are to be used when requesting copies from NTIS. Their mailing address is: National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151. The CRREL reference numbers refer to the bibliography compiled by the Library of Congress by CRREL. The citations appear in the form 00-00... The first two digits refer to the volume of the CRREL bibliography in which the citation appears. The numbers following the hyphen identify the specific citation. CRREL is located in Hanover, New Hampshire.

Hopefully, the information contained in this bibliography will be of as much value to other investigators as it has been to me. Significant contributions to the effort of compiling and producing this bibliography were made by D. Baird of the Coast Guard Research and Development Center, N. Dumont of CRREL, and M. Arthur of Sonalysts, Inc.

Paul Greisman
August 1980

# 1. Physical Properties of Ice

## A. Frictional

Dolov, M.A. and Makuashev, M.K., **Force of ice cohesion with some metals**, NTIS #AD-722 106, 1971, 8 pp., 7 refs., For original Russian article see CRREL#25-1741.

Based on analysis of test data, it is established that: (1) force of ice cohesion with various materials depends on the type of material, condition of its surface, and the temperature; (2) force of ice cohesion increases at a decrease in temperature and an increase in roughness of surface; and (3) force of ice cohesion depends on ice structure and rate of increase of external load. The faster the rate of load increase, the greater the value of cohesion force. At gradual loading, the viscous-plastic properties of ice are manifested.

Ericksson, R., **Friction of runners on snow and ice**, NTIS #AD-070 494, April 1955, 23 pp., 12 refs., Translation from Foreningen skogsarbetens och Kungl. Domanstyrelsens arbetsstudieavdening. Meddelandee No. 34/35:1-63, 1949.

Laboratory and field measurements of friction with metal and wooden runners on snow and ice are discussed. Sliding friction was determined by measuring the retardation of freely moving sleds, and initial friction was measured with a dynamometer. Coefficients of sliding friction varied from 0.006-0.3 and initial friction from nearly 0 to over 1. The coefficient of friction depends on the finish and dimension of the runner, air temperature, snow-particle size, water content of the snow, sliding speed, and stress. Friction usually increases with falling temperatures. Friction for steel runners doubled in the temperature range 0 to -30°C and increased for wooden runners up to 40 percent. Sliding depends largely on the lubrication effect of the water layer between the snow or ice surface and the runner.

Inaho, Y., **Angle of kinetic friction of snow**, NTIS #AD-070 493, January 1955, 5 pp., Translation from *Seppyo*, Vol. 3, pp. 303-307, 1941.

An attempt was made to measure the dynamic friction between snow and a slope from the acceleration of a block of snow sliding down an inclined plane. The construction of the apparatus used is described and formulas are developed for calculating acceleration and friction and the necessary corrections. The results are somewhat inconclusive because quality of snow cannot be expressed quantitatively. The data indicate that the angle of dynamic friction ranged from 23-29 degrees when a block of granular snow slides down a 3-m slope of granular snow.

Jellinek, H.H.G., **Adhesion of ice frozen from dilute electrolyte solutions**, NTIS #AD-776 370, March 1974, 9 pp., 10 refs.

Experiments by Smith-Johannsen on the adhesion of ice frozen from a number of electrolyte solutions to a wax-treated aluminum surface at -10°C are discussed. It is concluded that the adhesive strength measured by the force per sq. cm. needed to shear the ice off the substrate surface is mainly due to a liquid interfacial solution layer between the ice and the substrate surface. The thickness of such a layer is largely determined by the same considerations as the thickness of grain boundary layers in ice obtained from dilute electrolyte solutions.

Jellinek, H.H.G., **Adhesive properties of ice**, *Journal of Colloid Science*, Vol. 14, No. 3, June 1959, pp. 268-280, 20 refs.

Experiments on the adhesion of ice to stainless steel, polystyrene, and Lucite as a function of sample cross-sectional area, thickness, and temperature are described; the data are tabulated and graphed and the results are examined theoretically. The tests were made in special tensile and shear apparatus on snow-ice samples and ice directly frozen to the solid surface. Shear tests on snow-ice/stainless steel yielded pure adhesive breaks changing abruptly to cohesive breaks at a temperature of about -13°C. The adhesive strength of the system was a linear function of temperature and independent of the cross-sectional area and thickness of the samples in the ranges investigated. Ice/polystyrene gave pure adhesive breaks on shear, the adhesive strength being a linear function of temperature down to -15°C and independent of cross-sectional area. A linear relationship was found between adhesive strength and temperature from -2 to -25.5°C in tensile tests with ice/polystyrene, the cross-sectional area and the rate of stress application having no effect on adhesive strength. Ice/Lucite showed a larger adhesive stsrength than ice/polystyrene. The results are explained by the assumption of a liquid-like layer at the ice-solid interface, the thickness and consistency of which is a function of temperature and the nature of the solid surface. Surface tension forces and frictional forces operative in the liquid-like layer are discussed.

Jellinek, H.H.G., **Contact angles between water and some polymeric materials**, NTIS #AD-149 030, August 1957, 10 pp., 3 refs.

Measurements were made with 22 more or less hydrophobic polymers and lacquers at intervals of 5 or 10 min for periods up to 1 hr. All surfaces were carefully cleaned, and some surfaces were baked.

Highest initial (time 0) average contact angles (106 deg to 106.6 deg) were measured for Foster Snell rain repellent wax, Barrett 25-218 water repellent varnish (air-dried), and Cardolite NRL-7241. After 40 min, contact angles for these substances were 95.6 deg, 90.9 deg, and 91.0 deg. The measurement apparatus is illustrated, and data are tabulated.

Jellinek, H.H.G., **Ice adhesion,** *Canadian Journal of Physics*, Vol. 40, No. 10, October 1962, pp. 1294-1309, 27 refs.

Results of shear tests for the system ice-stainless steel and ice-optically flat fused quartz as a function of the rate of shear and roughness of the steel surfaces are presented. The adhesive strength decreased with decreasing roughness of the steel surfaces, and the force vs. time curves for smooth steel plates resemble those of two solids sliding over each other with a liquid layer between them. This behavior was especially evident in the case of the optically flat quartz. The adhesive strength as a function of rate of shear was linear for both ice-stainless steel and ice-quartz, but these were indications of yield values. The results agree with the assumption of a liquid-like layer on ice. Ratios of viscosity coefficient to layer thickness were evaluated for both systems, and viscosity coefficients estimated. Shear experiments on thin water films between glass plates support the assumption of a liquid-like layer on ice. The importance of interfacial free energy considerations is pointed out.

Jellinek, H.H.G., **Ice adhesion and abhesion: a survey**, National Research Council, Highway Research Board, Special Report No. 115, April 1970, pp. 46-47, 89 refs.

Article discusses ice adhesion, ice-air interface, ice-solid interface chemical properties, mechanical properties, and rheology.

University of Minnesota, Institute of Technology, Mechanical Engineering Department, **Friction on snow and ice**, NTIS #AD-084 888, June 1955, 186 pp., Includes appendixes, 372 refs.

Various theories of friction, particularly those related to snow and ice, are reviewed, and results of theoretical and experimental work begun in 1951 are discussed. Experimental data were obtained on the static and kinetic friction of sliders on ice and snow under various conditions of load, apparent area, material, temperature, humidity, time of stationary contact, and carriage velocity. It is concluded that the resistance to motion over compacted snow and ice is mainly a dry friction phenomenon relieved slightly by the presence of a film on the surface. The basic mechanism forming this film is probably either the frictional heating mechanism suggested by Bowden or the electrical dipole theory suggested by Weyl, although neither fully explains all frictional phenomena on ice and snow. The application of Weyl's dipole theory and preparation of a smooth, clear ice surface are included in the appendix. Suggested problems for future research are outlined.

## B. Floating Ice Forces

Ashton, G.D. and Calkins, D.J., **Passage of ice at hydraulic structures**, *Annual Symposium of the Waterways, Harbors, and Coastal Engineering Division of ASCE (3rd)*, Fort Collins, Colorado, 10-12 August 1976, and *American Society of Civil Engineers, Proceedings*, 1976, pp. 1726-1736, 32 refs.

The passage of ice through hydraulic structures is an important consideration in the construction of such works in the northern areas. The performance of various structures in passing ice has been documented mainly in descriptive terms; however, some physical measurements have been made on the volumetric ice discharge through such openings. By expressing the ice discharge as a surface concentration, meaningful site comparisons can be made. Physical model studies on various aspects of ice-related problems in rivers and at their structures have been increasing within the last five years. One major problem area is the assessment and influence of the strength of ice, which applies to both the field and laboratory studies.

Ashton, G.D., Kennedy, J.F., and Uzunef, M.S., **Two investigations of river ice: Part 1 - A field investigation of the formation and characteristics of river ice and Part 2 - Preliminary laboratory investigations of ice jams and navigation channels in ice covers**, University of Iowa, Iowa Institute of Hydraulic Research, Report No. 129, October 1970, NTIS #AD-728 114, 44 pp., 9 refs.

This article pertains to river ice, ice formation, temperature distribution, flow rate, ice jams, ice thickness, and ice breaking.

Assur, A., **Forces in moving ice fields**, *International Conference on Port and Ocean Engineering Under Arctic Conditions*, Proceedings, 1971, Vol. 1, pp. 112-118, 5 refs.

Forces that moving ice fields exert on structures depend upon size and shape of the structure ranging from isolated piles to straight walls and sloping cones. Broken-up ice causes additional design difficulties. Ice properties and failure modes must be considered.

Farrell, D.R., Haynes F.D., and Nevel, D.E., **Ice force measurement on the Pembina River, Alberta, Canada**, NTIS #ADA-018 223, October 1975, 12 pp., 12 refs.

Just before spring breakup in 1972, 23 in situ tests were conducted on the Pembina River in Alberta, Canada, to measure ice forces. These tests simulated an ice sheet pushing against a bridge pier. The apparatus utilized a hydraulic ram to push a 5 1/2-in. (14.0-cm)-wide vertical pile section horizontally against the ice sheet, which varied from 11.5 to 19.5 in. (29.2 to 49.5 cm) in thickness. The velocity of the pile was varied from 0.07 to 21 in./sec (0.18 to 53.3 cm/sec) by hydraulic flow control valves. Both flat and round piles were used to represent the pier. Some tests began with the piles a few inches away from the ice sheet, whose edge was cut flat. Other tests began with the pile in contact with the ice sheet. For some of the round pile tests, augered holes were used to provide better initial contact. These in situ test results were compared with the ice force measurement made by other workers on a nearby bridge during ice breakup. The in situ test forces were about 50% higher than the bridge pier test results. This disagreement was caused by a difference between the sizes of the piles and the size of the pier and a three-day warming of the ice before the ice impacted against the pier.

Goebeler, E., **Mechanical effects of lake ice**, Translation of Verhandlungen der Gesellschaft Erdkunde, Berlin, Vol. 18, January 1972, 12 pp., 3 refs.

The causes for the formation of fissures, ridges, and rafting of lake ice and their effects are discussed on the basis of 5-yr. observations in Germany. Fissures occur in a homogeneous ice cover in Jan.-Feb. as a result of the differential expansion of ice layers at different temperatures and usually precede the formation of ridges. Ridges are independent of currents and winds, forming generally in areas where the shoreline directly or indirectly impedes the free expansion of secondary ice in the fissures. The overthrust of larger ice masses over smaller ones is explained by the fact that the greatest pressures act from the direction of the larger mass. Ice ramparts up to 0.6 m high above the winter water level result from ice pressure.

Kennedy, J.F., Lee, C.L., Nakato, T. Tatinclaux, J.C., and Wang, T.P., **Laboratory investigation of the mechanics and hydraulics of river ice jams**, NTIS #ADA-032 471, April 1977, 44 pp., 7 refs.

This report presents experimental results on the conditions of initiation of an ice jam by a simple surface obstruction, on the equilibrium thickness of an ice jam formed by accumulation and submergence of ice floes, and on the compressive strength of a floating, fragmented ice cover. In the study on ice jam initiation, it was found that the minimum concentration of floes in the opening of the obstruction at which a jam occurs is nearly independent of the ratio of width of constricted passage to channel width and is proportional to a negative power of the ratio of flow length to width of constricted passage. The coefficient of proportionality and the negative exponent of this power function appear to be dependent upon the ratio of floe length to floe thickness and to be strongly affected by the properties of the material of the laboratory floes, in particular by the interparticle friction or cohesive characteristics. From energy analysis of floe submergence, a relationship between the thickness of a jam formed by accumulation and submergence of floes and the approach flow characteristics was derived and found to fit the experimental data satisfactorily. The relationship predicts that a stable jam cannot be formed when the approach flow velocity exceeds a

certain value. This phenomenon was observed experimentally, and the measured maximum values of approach velocity were found to be in excellent agreement with the predicted values. In both studies on jam initiation and development, it was found that surface tension, and therefore the wetting properties of the material used for small laboratory floes, has a significant effect on the submergence velocity of small floes, and should be taken into consideration when small-scale laboratory investigations of ice jam phenomena are conducted using floes made of artificial material. Experiments on compressive strength of floating, fragmented ice covers were conducted for ranges of cover length and cover thickness, using three different floe shapes and sizes. It was found that the compressive strength was inversely proportional to compression velocity and independent of cover length. The effect of cover thickness and floe shape or size remains unclear partly because of the limited ranges of thickness and floe size investigated and partly because of the experimental scatter in the results.

Kerr, A.D., **Bearing capacity of floating ice plates subjected to static or quasi-static loads**, *Journal of Glaciology*, Vol. 17, No. 76, 1976, pp. 229-268, In English with French and German summaries.

This paper contains a critical survey of the literature on the bearing capacity of floating ice plates. It consists of a discussion of general questions, a critical survey of analytical attempts to determine the bearing capacity of floating ice plates, and a survey of field and laboratory tests on floating ice plates and their relation to the analytical results. It concludes with a systematic summary of the results, a discussion of observed shortcomings, and suggestions for needed investigations.

Kerr, A.D., **Elastic plates with simply supported straight boundaries, resting on a liquid foundation**, NTIS #AD-237 338, September 1959, 12 pp. and 1 p. appendix, 14 refs.

The deflection expression of an infinite plate subjected to a concentrated force is used with the "method of images" to obtain solutions for 6 plates with simply supported edges. The semi-infinite plate, the wedge-shaped plate, and its special case, the rectangular corner plate, are solved in closed form; and the infinite strip, the semi-infinite strip, and the rectangular plate are solved as rapidly convergent series. Behavior under a concentrated force is studied in more detail for the semi-infinite plate and the rectangular corner plate. Relationships for obtaining bending moments, shear forces, and reaction distributions, as well as derivatives of the kei-function with respect to r and theta, are given in the appendices.

Laskar, K. and Strenzke, K., **Ice thrust on shores of north German lakes and its effects**, NTIS #AD-769 728, August 1973, 7 pp. 8 refs.,

volume changes of the ice cover, or by ice thrusting due to wind action pushing the ice against the shore. The latter type predominates in Germany. A specific minimum basin area is a prerequisite for large-scale thrust action. Several cases of ice thrust on the Ploner Lake (Germany) are described. The ice blocks pile up parallel over each other along the shore and push inland.

Nevel, D.E., **A semi-infinite plate on an elastic foundation**, NTIS #AD-616 313, March 1965, 12 pp. and 2 pp. appendix, 7 refs.

The solution of the problem of a semi-infinite plate on an elastic foundation is presented. This problem occurs when a load is applied near the edge of a floating ice sheet. The equations are evaluated for an edge load, and the results are given in graphical form for the following: (a) the maximum deflection that occurs at the edge under the load, (b) the movement that causes the initial cracking of the plate, (c) the distance from the edge that the circumferential crack will occur, and (d) the moment that causes the circumferential crack. The same method of solution can be applied to an infinite strip on an elastic foundation with any combination of simple, rigid, or free support at the edges.

Nock, S. J. **Topological properties of some trellis pattern channel networks**, NTIS #ADA-034 824, December 1976, 54 pp., 24 refs.

The topological properties of 10 stream networks that have moderate to well-developed trellis drainage patterns have been compared with those expected in a topologically random population. Magnitude 4 subnetworks show a systematic departure from expectation that can be related to geological controls. A link type classification system was developed and a series of equations describing the probability of occurrence of link types in topologically random populations derived. Analysis of the link structure in the channel networks showed small but persistent deviations from expectation in the well-developed trellis pattern streams. The general conclusion is that the topologically random model is a very useful standard with which to compare real channel networks.

Perham, R.F., **Forces generated in ice boom structures**, NTIS #AD-775 822, January 1974, 36 pp., 10 refs.

Two ice booms in the St. Lawrence were instrumented to measure ice forces during the 1972-73 winter. Measurements were made by two systems and related data including ice thickness, wind, air temperature, and water velocity were measured. The winter was mild; forces measured in the shore anchor were 6 tons during a January thaw, 8 tons at spring breakup; a 24 ton load was measured at mid-stream in January. It occurred in the boom rope and not in the river bottom anchor rope, indicating that the anchor had

moved downstream. Ice booms underwent harsh treatment from ice action even at relatively light loads.

Perham, R.F. and Racicot, L., **Forces on an ice boom in the Beauharnois Canal**, Hanover, New Hampshire, 18-21 August 1975, *International Symposium on Ice Problems (3rd)*, and International Association of Hydraulic Research, Proceedings, 1975, pp. 397-407, 7 refs.

Ice booms are used to hasten the formation of a stable ice cover in early winter. Their main function is to reduce the area of open water where large amounts of ice floes and fragile ice can be generated. This ice, if uncontrolled, can cause an ice jam or blockage at power house intakes and restrict its generating capacity. A particular function of the forebay ice boom of the Beauharnois Power House is to prevent any ice upstream from moving down into the forebay. In the winter of 1974-75, CRREL obtained force measurements of both cross stream and downstream components in the forebay ice boom. The purpose of this paper is to report these forces and their variations. A limited amount of supplemental data such as water flow, ice thickness, and canal dimensions are provided. All of the information should help in the understanding of interaction between an ice boom and its ice cover.

Peschanskii, I.S., **Static pressure of sea ice**, NTIS #AD-769 727, August 1973, 5 pp., For original Russian article see CRREL #26-1963.

Static pressure in ice develops in an ice cover on sudden rise in the temperature. At this time, the ice expands, exerting pressure on the shore belt and the engineering structures located there. The more abruptly this occurs, the higher the pressure. This static pressure of sea ice depends not only on the value of temperature drop and speed of its effect, but also on the salinity of the ice and on its ultimate temperature. The effects of these changes in temperature, its speed, and the salinity in sea ice and freshwater ice (and the differences between the two types of ice) is discussed as well as the pressure distribution through the ice's thickness.

Sackinger, P.A. and Sackinger, W.M., **Shear strength of the adfreeze bond of sea ice to structures**, *Proceedings of POAC 77, International Conference on Port and Ocean Engineering Under Arctic Conditions (4th)*, 26-30 September 1977, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, pp. 607-613.

When an offshore structure is affixed to the sea floor in a region subjected to moving ice, the mode of failure of the ice as it impinges upon the structure can take several forms, depending upon the ice sheet and the structure profile. For an ice sheet composed of many separate ice floes, as one may encounter in Cook Inlet, most ice floes do not strike the structure head-on, and are deflected around the structure. Concern has been with the contrasting Arctic offshore situation, particularly in the shorefast ice, where an essentially continuous ice sheet may move against a structure. Ice failure can occur near the structure by compression and can also occur when the ice bends in flexure against sloping structures. Even with vertical structure surfaces, failure in flexure can be expected frequently, but the conical structure is to be preferred because it clearly induces this mode of failure. Less lateral force is transmitted to a structure of conical configuration.

Sokolov, I.N., **Resistance coefficient at the lower surface of an ice cover**, NTIS #AD-715 080, 1970, 3 pp., Translation from Meteorologiia: gidrologiia, 1960, No. 4, pp. 34-36, 1 ref.

The present article gives data on the value of the resistance coefficient for a flat lower surface of ice, obtained by experiments with small blocks of ice in the shape of rectangular plates. The test consisted of measuring the net force of ice blocks of given dimensions floating on the surface of the water with the current at different rates of flow. The resistance coefficient at the water-ice boundary was calculated from the test results.

## C. Rheology

Ackley, S.F., Campbell, W.J., Hibler, W.D., III, Kovacs, A., and Weeks, W.F., **Mesoscale strain measurements on the Beaufort Sea pack ice (AIDJEX 1971),** *Journal of Glaciology,* Vol. 12, No. 63, 1973, pp. 187-206, 21 refs., For another version see CRREL #27-515.

The deformation of a strain triangle ( 6 km x 8 km x 11 km) located on first-year ice in the Beaufort Sea was observed over a two-week period in March 1971. Significant strain events ( 1.5°o) were observed to occur during short ( 6 H) time periods. The long-term (one day or more) divergence rate varied between 0.04 and 0.08 x $10^{-3}$ $h^{-1}$. Short-term divergence rates showed values as high as 0.29 x $10^{-3}$ $h^{-1}$. The observed shearing motion indicated that the floes to the east were moving to the south relative to the floes to the west. This agrees with the shear pattern that might be expected considering the location of the station in the Pacific Gyre. Studies of fracture (lead and crack) orientations in the vicinity of the strain triangle indicate reasonable correlations with the orientation of the strain-rate ellipse. A qualitative relation is suggested between the fracture density and the long-term divergence rate. Correlations were also observed between the divergence of the wind field as computed from the surface pressure field and the ice divergence.

Anderson, D., **Heat of freezing and melting of sea ice,** NTIS #AD-640 151, July 1966, 15 pp., 16 refs.

Computations are presented which show that the latent heat of freezing ice in equilibrium with sea water is less than that associated with freezing pure water of 0°C. The difference is due primarily to a temperature effect that is opposed to some extent by the effect of dissolved substances in the brine. The difference probably amounts to about 7 cal/gm of ice for a brine of about 150 per mill salinity, freezing at -8°C. When the effect of this difference in the total heat required to raise the temperature and melt sea ice is computed by Schwerdtfeger's method, it is found to be of the order of 0.5 cal/gm of sea ice for an overall ice salinity of 8 per mill and an initial temperature of -8°C. The differences are small but significant and until true values are established, published values of heats of freezing and melting and specific heats of sea ice should be used with discretion.

Anderson, D.L. and Weeks, W.F., **Theoretical analysis of sea-ice strength,** *American Geophysical Union, Transactions,* Vol. 39, No. 4, August 1958, pp. 632-640, 15 refs.

For the first time an attempt is made to derive a theoretical relationship between sea-ice strength and the controlling factors of salinity, temperature, and density. A geometric model of the ice-brine relationship is constructed from photographs and used to calculate tensile strength of warm (above -20°C) sea ice. The theoretical results compare well with experimental data. The model developed can be extended to colder temperatures by considering the effect of solid salts.

Assur, A., **Bearing capacity of floating ice sheets,** *Engineering Mechanics Division Journal,* American Society of Civil Engineers, June 1961, pp. 63-66, 3 refs.

Meyerhof's calculation of the collapse of ice sheets is criticized on the basis of field and laboratory work conducted by USA CRREL. That the idealized stress distribution leading to the full plastic bending movement does not correspond to the actual stress in an ice sheet may hold for fresh ice and quick loading, but may be proper for prolonged loading and especially for sea ice. The assumption that the hydrostatic reaction is confined within the hinge circle is unfounded, since experiments indicate considerable deflection at the circumferential hinge until collapse occurs. The assumption that the hinge radius is equal to the radius of the deflection dish is also incorrect. The circumferential crack occurs well within the deflection radius and at the place where the elastic theory predicts maximum radial stress. The conditions for this location are calculated and also considered on the basis of A. Johansen's concept of yield lines. Actual tests show a considerable deflection at the circumferential crack. Many other approximations were used even though more precise approaches can be derived.

Assur, A., **Flexural and other properties of sea ice sheets,** *International Conference on Low Temperature Science, Proceedings,* Vol. 1, Part 1, Institute of Low Temperature Science, Hokkaido University, 1967, pp. 557-567, 5 refs.

Article pertains to sea ice, flexural strength, ice cover strength, ice mechanics, and analysis (mathematics).

Assur, A. and Nevel, D.E., **Crowds on ice,** NTIS #AD-681 214, October 1968, 4 pp., 2 refs.

This report considers a floating ice sheet supporting a crowd of people who are free to assume any distribution. The problem is analyzed when the people gather into a long strip, two strips, or a circular area, all of which may vary in size. The worst possible size is determined for the safe bearing capacity in each case. Upon comparison of the results, a single equation is suggested for practical use.

Assur, A. and Weeks, W.F., **Fracture of lake and sea ice,** *Fracture: An Advanced Treatise, Vol. 1,* Liebowitz, H. (ed.), New York Academic Press, 1972, pp. 879-978, For another version see CRREL #25-990.

This article pertains to lake ice, sea ice, fracturing, ice cover strength, ice crystal structure, ice formation, compressive strength, tensile strength, and flexural strength.

Assur, A. and Weeks, W.F., **Mechanical properties of sea ice**, NTIS #AD-662 716, September 1967, 80 pp., 199 refs.

This review discusses the state of thinking of each of the main national groups investigating sea ice and gives an overall appraisal of the field as a whole. Emphasis is placed on: (1) the physical basis for interpreting sea ice strength (phase relations, air volume, and structural considerations), (2) theoretical considerations (strength models, air bubbles and salt reinforcement, and interrelations between growth conditions and strength), (3) experimental results (tensile, flexural, shear, and compressive strength, elastic modulus, shear modulus and Poisson's ratio, time dependent effects, and creep), and (4) plate characteristics. The paper includes a review of problems in sea ice investigations, relates the chemical, crystallographic, mechanical, and physical aspects involved, and concludes by showing how to utilize this knowledge to solve practical problems.

Butkovich, T.R. and Landauer, J.K., **Creep of ice at low stresses**, NTIS #AD-653 135, August 1960, 6 pp., 16 refs.

Uniaxial compression tests were made on 2x2x6 cm samples of large-grained commercial ice and small-grained glacier ice at temperatures from -1.3 to -18.9°C and stresses down to about 10,000 dynes/sq. cm, using a special apparatus to permit simultaneous measurement of 3 samples at different stresses. The uniaxial stresses and strain rates were reduced to shear stresses and strain rates by dividing and multiplying, respectively, the former by sq. root of 3. The log shear strain rate vs log shear stress curve was essentially linear for the low-stress creep measurements. Assuming a linear flow law for low-stress creep, activation energies for creep of about 14,300 cal/mole were determined. The smaller-grained ice had a higher viscosity coefficient than the larger-grained ice. The observed activation energy for creep of ice is probably that for self-diffusion. Although lacking a concrete deformation mechanism, the rate process theory, which leads to a hyperbolic sine stress dependence, seems to best describe the experimental results.

Butkovich, T.R. and Landauer, J.K., **Flow law for ice**, *International Association of Scientific Hydrology*, Publication No. 47, 1958, pp. 318-327, 18 refs., For another version of this paper and abstract see CRREL 24-3214.

This article pertains to glacier flow, ice creep, creep properties, deformation, and shear modules.

Coon, M.D. and Mohaghegh, M.M., **Plastic analysis of Coulomb plates and its application to the bearing capacity of sea ice**, University of Washington, Seattle, Department of Atmospheric Sciences, Report No. Scientific-12, June 1972, 159 pp.

The report describes a method of correlating the bearing capacity of sandwich plates (Coulomb plates) with the bearing capacity of sea and lake ice.

Evans, R.J. and Untersteiner, N., **Thermal cracks in floating ice sheets**, *Journal of Geophysical Sciences*, Vol. 76, No. 3, 20 January 1971, pp. 694-703.

When the air temperature drops below the water temperature under a floating ice sheet, thermal cracks often occur. To acquire quantitative information on these cracks from an analytic point of view, the ice has been represented as a homogeneous elastic floating plate. The effect of thermal contraction then becomes equivalent to a lateral surface load. After the problem has been formulated in general terms, three special conditions which lend themselves to analytic treatment are considered: the wide ice sheet under conditions of plane strain, the narrow ice sheet under plane stress conditions, and the axisymmetric ice sheet. The first two lead to simple solutions that illustrate general effects, the third is of more practical significance. Typical stress distributions prior to cracking are shown and for particular numerical values, some of which are applicable to arctic sea ice; typical crack spacing is related to the temperature difference between the upper and lower surface. Finally, the assumptions on which the analysis rests are examined critically with regard to establishing the validity of the results and to indicate ways in which improvements in the analytic treatment can be made.

Garbaccio, D.H., **Creep of floating ice sheets, computer calculations**, Science Engineering Associates, Inc., San Marino, California, December 1968, 100 pp., Distribution limitation now removed.

Using a digital computer, calculations were made of the deformations and bending movements in a floating ice sheet. The ice behavior was described by a linear viscoelastic model consisting of a Maxwell and a Voigt element in series. Loading with circular symmetry uniformly distributed was applied to a plate of finite thickness described by Reissner theory. The effect of superposed loads describing aircraft landing gear was considered. Calculations were also made for a linearized approximation to the problem of a thin sheet described by a power creep law. The method was only partially successful because the time span of applicability was short.

Gongadze, D.N., **Some theoretical problems in the formation and movement of snow avalanches**, NTIS #AD-720 068, 1971, 16 pp., 10 refs., Translation from Akademiia nauk Gruzinskoi SSR. Institut geofiziki. *Trudy*, Vol. 13. 1954, pp. 161-174.

In the present paper an attempt is made to resolve certain questions of the statics and dynamics of snow avalanches on the basis of the data of the existing literature in the field and the analysis of the material accumulated by the author during high altitude expe-

ditions of the Institute of Geophysics of the Academy of Sciences Georgian SSR during the 1948-54 period.

Gow, A.J., Ricard, J.A., and Ueda, H.T., **Flexural strength of ice on temperate lakes--comparative tests of large cantilever and simply supported beams**, NTIS #ADA-054 218, April 1978, 14 pp., 9 refs.

Large, simply supported beams of temperate lake ice were found, generally, to yield significantly higher flexural strengths than the same beams tested in the cantilever mode. Data support the view that a significant stress concentration may exist at the fixed corners of the cantilever beams. Maximum effects are experienced with beams of cold, brittle ice substantially free of structural imperfections; for this kind of ice the strength difference factor, here attributed to the effect of stress concentrations, may exceed 2.0; that is, simply supported beams test a factor of 2 or more stronger than the same beams tested in the cantilever mode. In ice that has undergone extensive thermal degradation, the stress concentration effect may be eliminated entirely. Simply supported beams generally yield higher strengths when the top surfaces are placed in tension. This behavior is attributed to differences in ice type; the fine-grained, crack-free top layer of snow-ice, which constituted up to 50% of the ice cover in the current series of tests, usually reacted more strongly in tension than the course-grained crack-prone bottom lake ice.

Gow, A.J. and Williamson, T., **Rheological implications of the internal structure and crystal fabrics of the west Antarctic ice sheet as revealed by deep core drilling at Byrd Station**, NTIS #ADA-031 745, September 1976, 25 pp.

Crystalline textures and fabrics of ice cores from the 2,164-m-thick ice sheet at Byrd Station, Antarctica, reveal the existence of an anisotropic ice sheet. A gradual but persistent increase in the c-axis preferred orientation of the ice crystals was observed between the surface and 1,200 m. This progressive growth of an oriented crystal fabric is accompanied by a 20-fold increase in crystal size between 56 and 600 m, followed by virtually no change in crystal size between 600 and 1,200 m. Between 1,200 and 1,300 m the structure transforms into a fine-grained mosaic of crystals with their basal glide planes now oriented substantially within the horizontal. This highly oriented fine-grained structure, which persists to 1,800 m, is compatible only with a strong horizontal shear deformation in this part of the ice sheet. Rapid transformation from single- to multiple-maximum fabrics occurs below 1,800 m. This transformation, accompanied by the growth of very large crystals, is attributed to the overriding effect of relatively high temperatures in the bottom layers of old ice at Byrd Station rather than to a significant decrease in stress. The zone of single-maximum fabrics between 1,200 and 1,800 m also contains numerous layers of volcanic dust. Fabrics of the very fine-grained ice associated with these dust bands indicate the bands are actively associated with shearing in the ice sheet. Some slipping of ice along the bedrock seems likely at Byrd Station, since the basal ice is at the pressure melting point and liquid water is known to exist at the ice/rock interface. The textures and fabrics of the ice indicate that plastic deformation (intracrystalline glide) in the zone of strong single-maximum fabrics, and movement of ice along discrete shear planes situated well above bedrock, are also major contributors to the flow of the ice sheet. Any extensive shearing at depth could seriously distort stratigraphic records contained in the ice cores, such as climatic history inferred from stable isotope analysis. Also, the common practice of using simplified flow models to approximate the depth-age relationships of deep ice sheet cores may need to be revised in light of the deformational features and fabrics observed in the Byrd Station ice cores.

Hawkes, I. and Mellor, M., **Deformation and fracture of ice under uniaxial stress**, *Journal of Glaciology*, Vol. 11, No. 61, 1972, pp. 103-131, 34 refs., In English with French and German summaries.

Techniques for making precise uniaxial tests for strength and deformability of ice are described. Results are given for tests made in uniaxial tension and uniaxial compression at constant displacement rate, using bubbly polycrystalline ice. These results include stress/strain curves, elastic moduli, rupture or yield strengths, and failure strains, all for a range of strain-rates. A few results for ice doped with hydrogen flouride are also given. The fracture mechanism for ice is discussed, and the test results are compared with data reported by previous investigators.

Haynes, F.D. and Mellor, M., **Measuring the uniaxial compressive strength of ice**, *Journal of Glaciology*, Vol. 19, No. 81, 1977, pp. 213-223, 7 refs., In English with French and German summaries.

An attempt was made to develop a simple but accurate method for making compressive strength tests on right circular cylinders. Compliant loading platens were designed to apply uniform normal stress without introducing significant interface radial shear stresses. The compliant platens gave reproducible results that agree well with results obtained by a precise conventional technique. Accurate results were obtained with simple specimen preparation, and with short specimens where the length-to-diameter ratio was less than unity. Platens were made from a rubber-like urethane that was molded in aluminum cylinders to provide lateral restraint. Uniaxial compression tests on cylindrical polycrystalline ice specimens were made to determine the characteristics of the platens. For 21 specimens with ends prepared on a lapping plate to obtain a mirror finish, the measure strength showed a variation of only 13% for length-to-diameter ratios

from 0.74 to 2.5, with no systematic trend. Another 21 specimens with length-to-diameter ratios of about 2.35 were tested with various platens and various methods of specimen end preparation. The strength for specimens with saw-cut ends and for those with ends lapped showed very little difference when tested with the rubber platens.

Haynes, F.D. and Nevel, D.E., **Interpretation of the tensile strength of ice under triaxial stress**, *International Conference on Port and Ocean Engineering Under Arctic Conditions (3rd)*, Vol. I, 11-15 August 1975, Fairbanks, Alaska, University of Alaska, 1976, pp. 375-387, 12 refs.

Griffith, and later Babel, have previously developed a tensile fracture criterion for a two-dimensional state of stress. This theory is extended to the compression-compression regions. From this theory the angle of fracture is developed. For uniaxial compression, the angle may be anywhere from 0 to 30 degrees measured from the direction of loading, depending upon the shape of the cavity. The theory is extended conceptually to three dimensions. Triaxial test data by Haynes for snow-ice are shown in this three-dimensional fracture theory. The test data are slightly less than that predicted when the void in the snow-ice is spherical.

Hendrickson, G. and Rowland, R., **Strength studies on antarctic sea ice**, NTIS #AD-622 773, July 1965, 20 pp., 5 refs.

The strength of sea ice was studied at McMurdo, Antarctica, during two successive field seasons. Three hundred tensile tests were made on continuous core samples taken at various locations on ice aged 1 year, 2 years, and more than 5 years. Salinity profiles were obtained for each core. A relationship between strength (kq/sq cm) and volume of brine cavities (percent), as suggested by Assur, adequately represents the data for brine volume approaching the value for fresh-water ice. The model on which the above expression is based apparently breaks down at high brine volumes.

Hibler, W.D., III, **Viscous sea ice law as a stochastic average of plasticity**, *Journal of Geophysical Research*, Vol. 82, No. 27, 20 September 1977, pp. 3932-3938, 17 refs.

This article pertains to sea ice, ice deformation, models, and plasticity tests.

Hoskins, R.R., Metzner, R.C., Nelson, R.D., and Shapiro, C.H. (University of Alaska, Geophysical Institute, Fairbanks, Alaska), **In-situ measurement of the mechanical properties of sea ice**, *American Society of Mechanical Engineers Paper*, presented at the ASME Petroleum Division: Energy technology conference and exhibition, Houston, Texas, 5-9 November 1978, 8 pp.

Techniques for conducting measurements of several of the mechanical properties of sea ice by in-situ methods are described. The tests described all involve the use of flatjacks of various shapes for supplying a known load onto the ice. The geometry of the sample being tested is defined by introducing internal boundaries into the ice sheet by cutting slots or installing layers of plastic film. The resulting deformation of the ice is measured by strain gauges embedded in the test sample, or by LBDTs of linear potentiometers mounted on pegs which, in turn, are frozen to some depth in the sample. Procedures for conducting uniaxial and biaxial compression tests, indirect tension tests, and a simulated direct shear test are described. These yield information on Young's modulus, Poisson's ratio, creep properties, and strength under various loading conditions.

Iakunin, A.W., **Calculation of ice-cover bending allowing for viscous properties of ice**, NTIS #AD-002 378, September 1978, 9 pp., 4 refs., For original Russian article see CRREL #26-2382.

This paper considers the linear viscoelastic deflections and stresses of a floating ice sheet. Young's modulus is replaced with a Maxwell model in series with a Voight model. The resulting differential equation is solved when the applied load is independent of time and is linear with time. No numerical results are given, but the author claims the resulting equations agree with experiments conducted on the Novosibirisk Reservoir.

Ivanov, K.E. and Lavrov, V.V., **Peculiarity of the mechanism of the plastic deformation of ice**, NTIS #AD-718 776, 1951, 3 pp., Translation from Zhurnal tekhnicheskoi fiziki, Vol. 20, No. 2, 1950, pp. 230-231.

It is well known that crystalline bodies differ from amorphous bodies, not only because they are anisotrophic, but also because of their special behavior in plastic deformation. The latter in crystals occurs in leaps and bounds and, as a result, the deformation curves clearly show this step-like characteristic. Up till now, this phenomena had been discovered in the crystals of NaCl, brass, zinc, and cadmium, and also in metals in the polycrystalline state (as brass and aluminim). It is shown that this peculiarity is also present in ice.

Kaplar, C.W., **Laboratory determination of the dynamic moduli of frozen soils and ice**, *International Conference on Permafrost, Proceedings*, 11-15 November 1963, Lafayette, Indiana, Publication 1966 1287, pp. 293-301, 22 refs.

Vibratory nondestructive techniques can be applied successfully in the laboratory to the study of dynamic elastic properties of frozen soils and ice. The dynamic moduli and wave transmission velocities of frozen soils increase with a decrease in temperature.

Below 20°F, the dynamic properties of fine-grained soils were more temperature dependent than those of coarse-grained soils. Elastic moduli for coarser-grained soils were more than 4 times those for fine-grained soils and ice. The dynamic elastic properties of ice, including wave velocities, were consistent with findings of other investigators.

Kerr, A.D., **Bending of circular plates confining an incompressible liquid**, NTIS #AD-640 887, August 1966, 8 pp., 4 refs.

Frozen potholes subjected to lateral loads suggest the study of the effect of the confined incompressible liquid upon the behavior of the covering ice plate. Since, for loads of short duration, no creep is expected, the plate may be assumed to behave elastically. The method of solution is described and two examples are treated in detail. A comparison of numerical results shows the strong effect of the confined incompressible liquid upon the deflections and stresses of the plate.

Korunov, M.M., **Approximate method of determining the carrying capacity of ice cover**, NTIS #AD-766 171/3, January 1973, 11 pp., Translation of Naucho-Issledovatel'skii Institut lesnoi Promyshlenmosti, *Trudy*, Vol. 3, 1967, pp. 122-129.

This article pertains to ice bearing capacity, ice cover thickness, dynamic loads, vehicles, and analysis (mathematics).

Kovacs, A., **Density, temperature and the unconfined compressive strength of polar snow**, NTIS #AD-660 309, July 1967, 25 pp., 19 refs.

The relationships between several empirical and theoretical methods of determining the unconfined compressive strength of polar snow from depth-density and temperature profiles are discussed and graphically compared. Two unconfirmed compressive strength equations are proposed for snow at -10°C. The formulas take into consideration the decided changes in slope of the Young's and shear modulus curves at a density of 0.5 g/cu cm for Greenland snow. The slope changes signify that at this density a structural and, therefore, a strength change occur. Analysis of existing test data confirms this reasoning.

Langleben, M.P., **Young's modulus for sea ice**, *Canadian Journal of Physics*, Vol. 40, No. 1, 1962, pp. 1-8.

A study is made of the dependence of Young's modulus for small samples of sea ice on their brine content. Young's modulus is determined from the velocity of ultrasonic waves through the samples and the brine content from their salinity and temperature. It is found that, over a range of brine content of about 0.01 to 0.1 as a fraction of the total volume, Young's modulus decreases linearly with increasing brine content. Its value is $10.0 \times 10^{10}$ dyne cm$^{-2}$ when the brine content is 0 and $6.5 \times 10^{10}$ dyne cm$^{-2}$ for a brine content of 0.1.

Lee, T.M., and Smith, J.L., **Complex Poisson's ratio dilatation constants from forced vibration of a sphere**, NTIS #AD-614 461, February 1965, 12 pp., 3 refs.

Following previous investigations on methods of determining dynamic mechanical properties of viscoelastic materials employing forced vibration, this report proposes a similar technique for determining the complex Poisson's ratio and the complex dilatation constants. Through the study of forced vibration of a free viscoelastic sphere with an internal harmonic oscillating source, it is found that these properties of the test material are related to the ratio of the vibration amplitude of two measurable points. Thus, when using the criterion of this ratio approaching its maximum, the maximum amplitude ratio, these properties can be expressed in simple relationship with laboratory-measurable quantities, namely the maximum amplitude ratios and their corresponding vibration frequencies. Investigations have been carried out for three sphere sets.

Mellor, M. and Smith, J.H., **Creep of snow and ice**, NTIS #AD-649 867, December 1966, 13 pp., 23 refs.

Constant load creep tests in uniaxial unconfined compression were performed on samples of sintered snow and bubbly polycrystalline ice. Nominal axial stresses were in the range 0.1 to 1.0 kgf/sq cm for snow, and 0.5 to 20 kgf/sq cm for ice. The range of temperatures investigated was from -0.5 to -34.5°C. Assuming creep to follow the Arrhenius relation, values of apparent activation energy for secondary creep under a nominal axial stress of 0.5 kgf/sq cm varied from 10.7 kcal/mole for ice of density of 0.83 g/cu cm to 17.8 kcal/mole for snow and density 0.44 g/cu cm. An equation is presented relating the dependence of strain rate on stress for polycrystalline ice through a range of stresses and temperatures. It is suggested that the creep of polycrystalline ice depends on at least two distinct mechanisms in the stress range studied. If each mechanism has its own characteristic activation energy, the apparent activation energy, measured in creep experiments may well vary with stress level. In snow subjected to a given nominal stress, such an effect should be reflected in variation of apparent activation energy with bulk density.

Mellor, M. and Smith, J.H., **Strength studies of snow**, NTIS #AD-631 717, January 1966, 21 pp., 14 refs.

Strength measurements are made on some 650 samples of homogeneous snow prepared under controlled conditions, primarily to investigate the effect of temperature variation. Comparative measurements were made on ice and frozen sand, and the variation of ram hardness with temperature was examined. An

equation is derived to express the relationship between rupture strength and temperature of the snow samples studied. An equation representing the effects of density variation for temperature in snow and ice samples is also given. However, because of inadequate density measurements for describing grain structure, the derivative for ice is questionable.

Mellor, M. and Tests, R., **Creep of ice under low stress**, *Journal of Glaciology*, Vol. 8, No. 52, February 1969, pp. 147-152, 5 refs., Includes summaries in French and German.

Uniaxial compressive creep tests on fine-grained polycrystalline ice indicate that secondary strain-rate is proportional to sigma exp (1.8), where sigma is applied stress, for the range 0.1 smaller than sigma smaller than 0.5 kgf/sq cm (10 smaller than sigma smaller than 50kN/sq m). On the basis of the present tests, earlier results suggesting linear viscous behavior at low stress are believed to be invalid.

Milne, A.R., **Thermal tension cracking in sea ice: a source of underice noise**, *Journal of Geophysical Research*, Vol. 77, No. 12, April 1972.

A summary is given of the important observations that relate the rheological properties of sea ice to the occurrence of surface tension cracks and explain how the noises produced by myriad surface cracks are observed under the ice. Ice-cracking noise is expected where the surface of the sea ice is cold and has a sufficiently low salinity to approximate a brittle solid. This condition is more likely to occur in seas covered by a high percentage of multi-year ice and where wind-mixing in leads was absent when the seas congealed. The acoustic water waves observed from crack-excited plate waves are described and two examples of single-frequency Crary wave arrivals are shown. A mechanism is postulated to explain the tendency for regularity in the spacing of pressure ridging in the Arctic Ocean. Thermal pre-stressing at the ice surface, added to flexural stresses caused by wind-induced flexural-gravity standing waves, can produce significant tensile stress maximums at antinode spacings. For 3 meters of ice, the predicted antinode spacings are 132 meters where a high probability of through-the-ice fractures can occur. Flexural-gravity waves that propagate in the presence of thermal pre-stressing should produce a correlation of wind speed with ice-cracking noise.

Nelson, R.D., **Internal stress measurement in ice sheets using embedded load cells**, University of Alaska, Geophysical Institute, Fairbanks, Alaska, pp. 361-373.

The interaction of an elastic inclusion and a stressed viscoelastic host is discussed as a means for stress analysis in sea ice sheets. A simple technique is presented that allows numerical calculation of both the elastic and the steady state viscoelastic responses of the inclusion. The behavior of a 4-node finite element model of host/transducer interaction is used to establish criteria for transducer design.

Nevel, D.E., **Creep theory for a floating ice sheet**, NTIS #ADA-026 122, June 1976, 98 pp., 73 refs.

The problem investigated is the prediction of the deflection and stresses in a floating ice sheet under loads that act over a long period of time. A review of analytical methods for predicting the bearing capacity of an ice sheet is given. The problem is formulated by assuming the ice is isotropic with a constant Poisson's ratio. The shear modulus is assumed to obey a linear viscoelastic model. The specific model selected is a series of one Maxwell model and two Voigt models. One of the Voigt models has a negative spring constant that produces tertiary creep. The ice model exhibits a primary, secondary, and tertiary creep response, similar to that observed in uniaxial creep tests of ice. The material properties in the viscoelastic model may be a function of the vertical position in the ice sheet, but all these material properties must be proportional to the same function of position. Using the thin-plate theory for the floating ice sheet, the solution is obtained for the deflection and stresses in the ice sheet for primary, secondary, and tertiary creep regions. It is then shown that for a load that is not distributed over a large area, the time-dependent part of the deflection and stresses is relatively independent of the load's distribution. For the elastic case, the stress significantly depends upon the load's distribution. Results are given for the deflection and stresses as a function of time and distance for the load. The maximum deflection and stresses occur at the center of the load. At this point the deflection increases with time, while the stresses decrease.

Nevel, D.E., **Ultimate failure of a floating ice sheet**, *Symposium of Ice and Its Action on Hydraulic Structures (2nd)*, Vol. 1, 26-29 September 1972, Leningrad, pp. 17-22, 9 refs.

When a floating ice sheet impinges on a sloping structure, the ice will fail in bending. To obtain a theoretical approach to this problem, a review is given of the way in which a vertical load will ultimately break through the ice. New theoretical equations are given for the breaking of wedges and the results compare favorably with published data on the ultimate load carrying capacity of ice sheets. For a sloping structure, a wedge with both vertically and horizontally applied loads has been solved, but numerical results are still being calculated.

Norris, D.M., Jr. and Young, W.C., **Longitudinal forced vibration of viscoelastic bars with end mass**, NTIS #AD-707 925, April 1970, 25 pp., 6 refs.

A simple method is presented to measure the complex modulus of suitably rigid linear viscoelastic materials over the audio-frequency spectrum. The case is

considered where one end of a rod of the material is driven harmonically and the complex displacement ratio is measured. The effect of a rigid end mass on the free end is accounted for. It is shown that, at specific frequencies near resonance, it is easy to obtain modulus data with standard equipment usually found in the vibratory. An experimental program is described.

Panfilov, D.R., **On the determination of the carrying capacity of an ice cover for loads of long duration**, NTIS #AD-737 812, January 1972, 14 pp., 12 refs., Translation of Russia. Ministerstvo vysshego i srednego spetsial'nogo obrazovaniia, *Izvestia vysshikh uchebykh zavedenii*, No. 6, 1961, pp. 47-57.

This article pertains to ice bearing capacity, plastic deformation, ice plasticity, static loads, dynamic loads, and ice creep.

Panfilov, D.R., **Strength calculations of ice cover**, NTIS #AD-762 105, March 1973, 9 pp., 18 refs., For Russian original see CRREL #25-1594.

This article pertains to stress analysis, ice cover strength, flexural strength, ice cover thickness, transportation, and ice (construction material).

Pavlak, R.L. and Ramseier, R.O., **Unconfined creep of polar snow**, *Journal of Glaciology*, Vol. 5, No. 39, October 1964, pp. 325-332, 10 refs., French and German summaries.

Snow samples from Amundsen-Scott and Byrd Stations, Antarctica, and from Camp Century, Greenland, were tested for creep as a function of density under low stresses for various periods up to two years. Comparisons of compressive viscosities plotted against densities for all three sites showed three distinct regions representing three different mechanisms of densification. Viscosities increased up to densities of 0.47 g/cu cm and above 0.625 g/cu cm. Between these densities, compressive viscosities are nearly constant.

Stearns, S.R., **Flexural properties of snow and snow-ice**, NTIS #AD-610 143, October 1964, 8 pp. plus appendixes, 12 refs.

One testing objective was to determine if small, select samples of natural snow-ice, tested in bending, would provide consistent and higher values for the flexural strength and modulus of elasticity. Another objective was to investigate the surface bearing properties of snow-ice layers, formed during winter on lakes or rivers, which are often separated from clear ice by an interlayer of slush or water. Dense snow-ice at 5°C had high flexural strength (avg. 6.08 x 100,000 psi), probably the result of a large, interlocking crystal structure. The apparent relationship between modulus of elasticity and density of snow-ice is affected by the rate of loading and temperature. There appears to be a relationship between density and flexural strength for snow, snow-ice, and high density snow in the natural undisturbed state; but processing, including snow compaction, lowers the tensile strength at early ages. The formulas used in computations are given and test results are tabulated and summarized.

Takagi, S., **Viscoelastic deflection of an infinite floating ice plate subjected to a circular load**, NTIS # ADA-054 896, April 1978, 32 pp., 19 refs.

The viscoelastic deflection of an infinite floating ice plate subjected to a circular load is solved, assuming the Maxwell-Voigt type four-element model. An effective method is developed for numerical integration of the solution integrals, of which each integrand contains a product of Bessel functions extending to infinity. The theoretical curve is fitted to the field data, but the material constants thus found varied with time and location.

Vialov, S.S., **Laws of ice deformation**, NTIS #AD-715 032, 1970, 15 pp., Translation of Zakonomernosti deformirovaniia l'da. Sov. antarktich eksp. 2nd, Gliats. issled., No. 10, 1960, pp. 239-248.

During the Second Continental Expedition, a special laboratory was created to carry out ice deformation tests. These included compressive tests with and without lateral extension, shear tests, and hardness tests. Ice having different structural characteristics was investigated. An analysis, including plots of ice compaction and flow as functions of crystal orientation, time, and loading conditions, is presented. Elastic deformations on ice have a twofold nature - pure elastic deformation occurring instantly and an elastic aftereffect developing with time.

Vialov, S.S., **Visco-plastic flow of glacial covers and the laws of ice deformation**, NTIS #AD-715 031, 1970, 28 pp., 8 refs., Translation from Issledovaniia pofizike i mekhanike merzlykh gruntov, No. 4, 1961, pp. 137-155.

Results of investigations carried out during the Second Antarctic Expedition (1956-1958) are reported. The first part deals with various experiments at the Mirnyy base camp on the creep, compression, shear, and hardness of ice under different test conditions. Data are analyzed mathematically. The second part covers the flow of ice sheets. Earlier studies are mentioned. Calculated data are compared with actual measurements between the Mirnyy camp and Vostok in E. Antartica and are found to be in good agreement as regards surface configuration and in satisfactory agreement with respect to the rate of flow.

Weeks, W.F., **Tensile strength of NaCl ice: a summary**, *Arctic Planning Session, Proceedings (3rd)*, November 1960, pp. 95-101, 4 refs.

This article pertains to sea ice, tensile strength, salinity, and brines.

Weeks, W.F., **Tensile strength of NaCl ice**, *Journal of Glaciology*, Vol. 4, No. 31, March 1962, pp. 25-52, 26 refs., French and German summaries.

Ice samples from fresh water and at salinities ranging from 1-22 per mill were prepared in a tank designed to simulate the one-dimensional cooling of natural water bodies. Phase and density relations were computed for these salinities in the temperature range 0 to -35°C and a determination made of the dependence of ring-tensile strength of the ice samples on temperature, brine volume, and thermal history. The results indicate that the strength of fresh water ice is essentially temperature independent in the temperature range -10 to -30°C. The strength of salt ice at temperatures between -5°C and the eutectic point (-21.2°C) decreases with an increase in the volume of brine in the ice and can be considered a unique function of brine volume, independent of the individual temperature and salinity values. It is suggested that the strength of fresh water ice should be considered as a limit that is approached but not exceeded by salt ice.

## D. Ice Strength

Anderson, D.L. and Weeks, W.F., **Experimental study of strength of young sea ice**, *American Geophysical Union, Transactions*, Vol. 39, No. 4, August 1958, pp. 641-647, 10 refs.

Results of in-place cantilever beam tests presented in this paper show a definite relationship between flexural strength and brine content. Values for Young's modulus are also experimentally determined. It is shown that the bearing capacity of a sea-ice sheet is dependent on the brine content and that thin ice sheets are capable of supporting a large 'super load' beyond the force necessary to form the first crack.

Assur, A., **Composition of sea ice and its tensile strength**, NTIS #AD-276 604, December 1960, 49 pp., 30 refs.

Part of the salts contained in sea water are trapped in sea ice upon freezing. They form liquid and solid inclusions in a systematic pattern. The amount depends upon temperature and salinity. A detailed table of phase relations is given and a general theory is derived to show how the internal cavities may affect the strength of sea ice. The general theory leads to specific models. The principle of ring tensile strength tests is explained and a series for evaluation is given. Test data lead to a substantiation of theoretical principles and to an illustration of several hypotheses concerning the effect of solid salt inclusions upon strength. Observed sea ice phenomena are explained on the basis of internal structure.

Assur, A., **Criteria for landing bomber and fighter aircraft on floating ice sheets**, NTIS #AD-317 509, April 1959, 14 pp., 5 refs.

The purpose of this paper was to formulate the principles leading to the calculation of the required ice thickness under varying conditions and, to place the necessary operational criteria for some military aircraft.

Assur, A., **Sea ice engineering**, *International Conference on Port and Ocean Engineering Under Arctic Conditions (3rd)*, 11-15 August 1975, Fairbanks, Alaska, Vol. 1, University of Alaska, 1976, pp. 231-234, Extended summary only.

This article pertains to sea ice, ice mechanics, and engineering.

Assur, A. and Weeks, W.F., **Structural control of the vertical variation of the strength of sea and salt ice**, Army Cold Regions Research and Engineering Lab., Hanover, New Hampshire, April 1964, 2 pp.

The vertical variation in the strength of sea ice was studied by using data from NaCl ice that shows a structural similiarity to sea ice and has straightforward phase relations. Measurements show that the plate spacing is a linear function of the sixth root of the distance below the upper ice surface (z). Available values of the same parameter for natural sea ice are in good agreement with this relation. Equations giving the dependence of the ring-tensile strength of the ice on z were developed. It is demonstrated that in NaCl ice sheets the systematic increase in the plate width with depth produces significant changes in the ring-tensile strength of the ice. Field tests previously performed indicate that similar relations hold for sea ice.

Boorke, A., Karelin, D.B., Stefansson, V., Volkov, G., and Zubov, N.N., **Investigation of construction of airdomes on ice, 1946-1947, Appendix B**, Arctic Construction and Frost Effects Lab, Boston, Massachusetts, May 1947, Report No: ACFEL-TR-8-App-B, 243 pp., translations.

Includes Trans-1, Sea Ice, by A. Boorke, Moscow, 1940; Trans-2, In the Center of the Arctic, by N.N. Zubov, Leningrad, 1940, with notes by Vilhajalmur Stefansson; Trans-3, Air Expedition to High Latitudes of the Arctic in 1941, by D.B. Karelin, publ, in Vsesoyuznoe Geograficheskoe Obshchestvo, Izvestiya (USSR), Vol. 77, No. 3, p. 16, 1945, and Trans-4, Airfields on Ice, by G. Bolkov, pub. in Morskoi Sbornik (USSR) No. 3, 1940, pp. 77-78. See also Appendix A, AD-712 473. Supersedes AD-141 181.

Butkovich, T.R., **Crushing strength of lake ice**, NTIS #AD-075 249, August 1955, 5 pp.

Tests were made to determine the effects of size of prismatic specimens, cross section, ratio of overall length to length of side of square section, types of ice, both natural clear ice and snow ice, orientation of c-axis, and size of candle. Rough-cut specimens were crushed in a 120,000 lb capacity press. The results of the tests show that: (1) Large-grained clear ice is stronger parallel to the ice sheet than normal to it; (2) Ice is stronger parallel to the ice sheet than normal to it; (3) Specimens of smaller cross-section have higher crushing strength; and (4) Prisms with lower ratios of length to width are stronger. No effect of c-axis orientation was detected.

Butkovich, T.R. and Landauer, J.K., **The flow law for ice**, NTIS #AD-235 263, August 1959, 7 pp., 18 refs.

The results of laboratory creep tests in a shear apparatus at -5°C on 2 x 2 x 3/8 in. samples of commercial ice, artificial single crystals, and 6 types of ice from the Greenland Ice Cap, at shear stresses of about 0.5 - 3 kg/sq. cm are reported. Some uniaxial tests were made at stresses from 6 - 28 kg/sq. cm to supplement the shear tests. Creep data could usually be represented approximately by one or more linear sections on a log-deformation vs log-time plot. The linear sections of the double logarithmic curve imply a creep curve of the form "e equals ct exp.m," where e is

the strain. For all samples tested, except single crystals sheared in easy glide, m averaged 0.5 for shear deformations up to about 1 percent, and approached unity for more deformation. For single ice crystals oriented for easy glide, m averaged 1.7, implying a strain softening. Single crystals oriented for hard glide behaved similarly to polycrystals, indicating a rate-controlling process such as dislocation climb. For all but single easy-glide crystals, the minimum creep rate was tangent to the deformation curve at the end of the experiment. Creep rates for single easy-glide crystals were several hundred times larger than for the other crystals, the flow laws being similar.

Butkovich, T.R., **On the mechanical properties of sea ice, Thule, Greenland, 1957**, NTIS #AD-235 872, August 1959, 11 pp. plus 9 pp. appends., 6 refs.

The investigations on sea ice, conducted at Thule, Greenland, during February and March 1957 included: unconfined compressive strength, ring tensile strength, and flexural strength tests on simple beams for both horizontal and vertical test specimens. Additional tests were made to determine the modulus of elasticity with the simple beams in flexure. Tests were also made for creep in uniaxial compression. Although there is a high scatter of results, a dependence of strength and creep on temperature and brine volume is evident. Higher compressive, tensile, and flexural strength, along with higher values of the elastic modulus were obtained at lower temperatures or brine volumes. The minimum creep rate decreases with decreasing temperature and brine volume.

Butkovich, T.R., **Some physical properties of ice from the Tuto tunnel and ramp, Thule, Greenland**, NTIS #AD-225 569, May 1959, 17 pp., 7 refs.

Results of unconfined compressive strength, ring tensile strength, and flexural strength tests are given. Crushing strength values for tunnel ice fit the empirical equation relating crushing strength to density, which was found for high-density snows. However, the values for ramp ice do not fit the equation when the average density values are used, probably due to the layering. The empirical equation relating ring tensile of high-density snows gives results 20 percent greater than those obtained for tunnel ice. Ice with large grains consistently gives lower values. Flexural strength of ramp ice is about half that of tunnel ice. Comparing these results with the ring tensile values leads to the conclusion that the beams tend to fail in the lowest-density (mostly bubbly) bands. Temperature curves as a function of depth into the wall and along the tunnel length are presented. A 30-day study of deformation in a 100 x 30 ft room at 650 ft into the tunnel indicated that the room is closing primarily by a block action, with rates of closure being less only very near the walls.

Butkovich, T.R., **Strength studies of sea ice**, NTIS #AD-125 593, October 1956, 15 pp., 6 refs.

Investigations on sea ice at Hopedale, Labrador, March 1956, included: small beam tests and in-place cantilever beam tests for flexural strength; ring tensile-strength tests; unconfined compression tests, with stress-strain studies to determine "Young's modulus"; and double shear tests. The results exhibit a great deal of scatter, primarily due to the inhomogeneity of sea ice. Ring tensile strength values range between 3.3 kg/sq. cm and 22.3 kg/sq. cm between -2.5°C and -19.1°C. The small beam tests give flexural strength values from 0.5 to 17.3 kg/sq. cm in a similar temperature range. The in-place pull-up cantilever beam tests give flexural strength values of 2.2 to 4.0 kg/sq. cm, with much less scatter. Crushing strength values range from 26.3 to more than 107 kg/sq. cm in the range -4.9°C to 18.3°C. Values for Young's modulus obtained from the slope of the straight line portion of the stress-strain curves in compression ranged between 4520 and 10,225 kg/sq. cm. There is a temperature dependence, explained by the effect of change in brine content, on sea-ice structure. The double shear tests give values of 7.8 to 34.2 kg/sq. cm in the range -5.5°C to -12.8°C. These are higher than the tensile-strength values. These failures occurred normal to the direction of growth, while the tensile strength was obtained with failure parallel to it.

Bukovich, T.R., **Ultimate strength of ice**, NTIS #AD-050 514, December 1954, 12 pp., 10 refs.

The crushing and torsional shear strengths of clear lake ice, natural snow ice, and commercial artificial ice, as well as the tensile strength of commercial ice, were measured in the laboratory. Data were tabulated and graphed, and earlier results obtained by different investigators are reviewed. Specimen shape influenced crushing-strength values, with machined cylindrical specimens yielding the highest values. Crushing strength parallel to the ice sheet was about 75 percent of that normal to the ice sheet for clear lake ice, but differences between the two orientations were insignificant for natural snow ice. Values obtained for commercial ice were slightly lower than those for clear lake ice. Torsional shear strength for clear lake ice showed a strong temperature dependence as well as anisotropism between shear and orientation, while for snow ice temperature dependence was weak and anisotropism absent. Tensile strength for commerical ice increased linearly with decreasing temperatures to -40°C; a sudden increase in strength occurred with further temperature lowering.

Coon, M.D., **On wind induced cracking of sea-ice sheets**, *AIDJEX Bulletin*, No. 29, University of Washington, Seattle, July 1975, pp. 131-134, refs.

In a paper by Weber and Erdelyi (AIDJEX Bulletin No. 28, March 1975), it was postulated that wind-induced tilt could cause ice sheets to break at right

angles to the direction of drift, and it was assumed that the ice floes are rigid. In this paper, it is demonstrated by means of calculations that a first approximation of behavior of ice sheets is that of a floating elastic plate. The incorporation of flexural behavior into the analysis of the ice leads to the conclusion that fracture of ice as a result of wind loading is impossible not only for the case of semi-infinite plates, but also for finite length plates.

Coon, M.D., Maykut, G.A., Pritchard, R.S., Rothrock, D.A., and Thorndike, A.S., **Modeling the pack ice as an elastic-plastic material**, *AIDEX BULLETIN*, No. 24, University of Washington, Seattle, Department of Atmospheric Sciences, May 1974, pp. 1-106.

A model of the motion of drifting pack ice in the Arctic Ocean is presented, treating explicitly, if not with consistent rigor, the growth and melt rates of the ice, the formation of leads and pressure ridges, and a mechanical response, which is elastic at low stress levels and plastic at some higher, critical state of stress. The strength of the ice is determined by this thickness distribution, and therefore varies because of both thermal and mechanical effects. To examine the behavior of the model, several idealized calculations were made by specifying the strain rate history of a single element of pack ice and solving for the ice thickness distribution and the states of stress in the ice.

Dykins, J.E., **Ice engineering-tensile properties of sea ice grown in a confined system**, Naval Civil Engineering Lab, Port Hueneme, California, Report No. NCEL-TR-689, July 1970, 63 pp.

Tensile strength envelopes were developed for horizontally and vertically oriented specimens of saline ice. The upper boundary limit in each case represents 1- to 2-ppt salinity ice for temperature range -4°C to -27°C, while the lower boundary represents 7- to 9-ppt natural seawater ice, which was grown in the laboratory, are closely identifiable with the characteristics of sea ice formed in a natural environment. This observation was based on comparison of the upper 44 cm of laboratory ice with a similar thickness of natural sea ice. The tensile strength was found to be a nonlinear function of temperature; there were strong implications, however, that a linear relationship with salinity may exist. The strength was found to be dependent on orientation of the stress field with both the grain (crystal) and subgrain (platelet) structure. Limited study indicates that the tensile strength of saline ice is appreciably reduced as stress rates increase above 25 psi/sec.

Evans, R.J., **Cracks in perennial sea ice due to thermally induced stress**, *Journal of Geophysical Research*, Vol. 76, No. 33, November 1971, pp. 8153-8155.

The lowering of surface temperature below that of the water temperature underneath a floating sea-ice sheet often results in thermal cracking. The formation of these cracks is investigated theoretically by modeling the ice sheet as a floating elastic plate with thermal properties that vary with temperature and salinity. Results are obtained by extending previous work of Evans and Untersteiner and a typical crack spacing on the order of 200 m is found for perennial sea ice.

Evans, R.J., and Untersteiner, N., **Thermal cracks in floating ice sheets**, *Journal of Geophysical Research*, Vol. 76, No. 3.

When the air temperature drops below the water temperature under a floating ice sheet, thermal cracks often occur. To acquire quantitative information on these cracks from the analytic point of view, the ice has been represented as a homogeneous elastic floating plate. The effect of thermal contraction then becomes equivalent to a lateral surface load. After the problem has been formulated in general terms, three special conditions which lend themselves to analytic treatment are considered: the wide ice sheet under conditions of plane strain, the narrow ice sheet under plane stress conditions, and the axisymmetric ice sheet. The first two lead to simple solutions that illustrate general effects, the third is of more practical significance. Typical stress distributions prior to cracking are shown and for particular numerical values, *some of which are applicable to Arctic sea ice;* typical crack spacing is related to the temperature difference between the upper and lower surface. Finally, the assumptions on which the analysis rests are examined critically with regard to establishing the validity of the results and to indicate ways in which improvements in the analytic treatment can be made.

Frankenstein, G.E. and Garner, R., **Dynamic Young's modulus and flexural strength of sea ice**, NTIS #AD-710 975, May 1970, 13 pp., 10 refs.

This report describes the results of tests made to determine the dynamic Young's modulus E of young sea ice. The ice samples were mainly parallelepipeas, but few were 7.62-cm-diam cores. The longitudinal wave velocity was determined by measuring the time required for a sound wave to travel the length of the sample. The measured wave velocities were corrected, by Love's frequency equation, to apply to infinite wavelengths. The flexural strength of the ice was determined by conducting a number of simple beam tests. The average value for the flexural strength was 11.3 kg/sq. cm.

Frankenstein, G.E., **Ring tensile strength studies of ice**, NTIS #AD-686 284, February 1969, 36 pp., 8 refs.

This paper gives the results of ring tensile strength tests of lake and sea ice. The sea ice tested was normal, low-salinity, and high-salinity. The strength

results plotted against the square root of the brine volume gave a least squares equation. A series of tests was conducted to test the theory that the concentration factor, K, for a solid cylinder is equal to 6. The average of the new K values computed from the test results is 5.2.

Frankenstein, G.E., **Strength data on lake ice**, NTIS #AD-236 204, December 1959, 6 pp. plus appends.

The results of in-place cantilever beam tests and small-beam tests with center loading, conducted in 1956-1957 on lake ice in Minnesota, Wisconsin, and Michigan, are reported; the testing procedures and equipment used are described; and the data are tabulated and graphed. The tests were made on clear ice, snow-ice (dense, medium, and rough), and a combination of clear ice and snow-ice. The flexural strength of snow-ice was unusually high when the bottom was in tension and low when the surface was in tension. The flexural strength of snow-ice was unusually high, especially when the surface ice was put in tension. The flexural strength of the combination of clear ice and snow-ice was approximatly the same whether the surface was in tension or compression, and higher than that of cold clear ice. No significant relation was found between temperature and strength. The strength values in small-beam tests were much higher than in in-place beam tests, but had a wider scatter. The flexural strength of clear ice in late winter or early spring with the surface layer in tension decreases at a faster rate than with the surface layer in compression.

Frankenstein, G.E., **Strength data on lake ice, II**, NTIS #AD-701 054, January 1961, 18 pp., 2 refs.

Results are reported of 245 in-place supported beam tests and 56 in-place cantilever beam tests conducted during the 1957-58 winter on clear ice and a combination of clear and snow-ice from Chassel and Keweenaw Bays (Mich.). The supported beams had a higher computed flexural strength than similar cantilever beams. The flexural strength of the supported beams with the surface layer in tension was always higher than the supported beams with the bottom layer in tension. As reported earlier, the flexural strength of cantilever beam tests was highest when the bottom layer was in tension. On a clear day with air and ice temperatures near 0°C, ice strength will decrease by as much as 6 times from morning to mid-aft. The testing equipment is illustrated, summary data are tabulated and graphed, and results of individual tests are appended.

Frankenstein, G.E, **Strength of ice sheets**, National Research Council, Canada, Associate Committee on Geotechnical Research, Technical Memorandum, March 1968, and proceedings of a conference held at Laval University, Quebec, 10-11 November 1966, pp. 79-87, 11 refs.

This paper describes the results of a number of large load tests performed on an arctic lake to gain further knowledge in determining the bearing capacity of floating ice sheets. The tests were two types: (1) distributed loads and (2) relatively concentrated loads. In the distributed load tests a 15-ft diameter aluminum tank, with a height adjustable to 20 ft, was placed directly on the surface. Lake water was pumped into the tank to load the ice. The concentrated load tests were conducted in the same manner as the distributed tests except that the tank was placed on a platform balanced on a 24 in. diameter wooden block. The deflection of the ice sheet was measured at the load and at various distances away from the load. A deflection profile for each test is included. The time of audible cracks and their position, if observed, were recorded. The elastic theory predicts the outer circumferential crack to be at a distance greater than 1.8L for a concentrated load. The observed location was inside 1.1L. In the concentrated tests a circumferential crack did not always form. There were always 13 radial type cracks present after each concentrated test.

Gow, A.J. and Langston, D., **Flexural strength of lake ice in relation to its growth structure and thermal history**, NTIS #ADA-020 964, December 1975, 28 pp., 13 refs.

In-place cantilever beam tests on Post Pond and Mascoma Lake ice yield a maximum flexural strength of 7.1 kg/sq cm. The minimum strength, unrelated to failure along pre-existing cracks in the ice, was 2.9 kg/sq cm. The majority of tests were performed in the push-down mode after it was discovered that beams tested in the pull-up mode, which places the bottom surface in tension, frequently broke prematurely along cracks in the bottom of the ice. Premature failures of this kind usually occurred at stresses of 2-3 kg/sq cm. Data further demonstrate that the intrinsic strength of lake ice decreases significantly as the surface air temperature goes to 0°C. Ice that has just become isothermal, but has not yet begun to candle, has a strength of about 4 kg/sq cm; ice that has been subjected to prolonged periods of above-freezing air temperatures generally fails at about 3 kg/sq cm. Tests also show that cold unrecrystallized snow-ice is as strong as the underlying lake ice. Tests of the effect of crystalline structure indicate that ice composed of crystals with their c-axes horizontal is measurably stronger than ice in which the crystals are oriented with their c-axes vertical.

Gow, A.J., **Flexural strength of ice on temperate lakes**, *Journal of Glaciology*, Vol. 19, No. 81, 1977, pp. 247-256, 7 refs., In English with French and German summaries.

Large, simply supported beams of temperate lake ice generally yield significantly higher flexural strengths than the same beams tested in the cantilever mode.

Data supported the view that a significant stress concentration may exist at the fixed corners of the cantilever beams. Maximum effects are experienced with beams of cold, brittle ice substantially free of structural imperfections; the stress concentration factor may exceed 2.0 in this kind of ice. In ice that has undergone extensive thermal degradation the stress concentration effect may be eliminated entirely. Simply supported beams generally test stronger when the top surface is placed in tension. This behavior is attributed to differences in ice type; the fine-grained, crack-free top layer of snow-ice usually reacting more strongly in tension than the coarse-grained bottom lake ice, which is prone to cracking.

Hawkes, I. and Mellor, M., **Measurement of tensile strength by diametral compression of discs and annuli**, *Engineering Geology*, Vol. 5, No. 3, 1971, pp. 173-225, 33 refs.

The validity of diametral compression tests for indirect measurement of tensile strength is investigated theoretically and experimentally. Linear elastic theory for diametral compression of discs and annuli by opposed strip loads is reviewed, and the significance of failure criteria in fracture initiation and test interpretation is considered. Results of careful tests are given for three types of rock, two plastics, glass, and ice, and the experimental results are compared with theoretical expectations. While there are very serious objections to the ring test, the Brazil test is capable of giving a good measure of uniaxial tensile strength for Griffith-type materials. Practical problems involved in diametral compression testing are considered in some detail. Special attention is given to contact stresses under the applied loads, and a design is given for a loading jig that reduces contact stresses. Specimen dimension, size effects, loading rate, force readout, and specimen preparation are discussed, and some recommended practical procedures for Brazil tests are outlined.

Hawkes, I., **Development and evaluation of an apparatus for the direct tensile testing of ice**, NTIS #AD-698 022, October 1969, 27 pp., 21 refs.

This report discusses the theory of the uniaxial tensile test of a brittle material and describes in detail the development and calibration of an apparatus designed to subject fine-grained polycrystalline ice specimens to uniaxial tensile and compressive loads up to failure, and to give a continuous stress-strain curve during the loading cycle. A technique for preparing fine-grained ice specimens is also given together with a preliminary tensile strength value (19.3 kg/sq cm) and stress-strain relationships (initial tangent modulus 5.6 x 100,000 kg/sq cm) at a temperature of 15°F and a strain rate of 3.6 x 10 to the -6th strain/sec.

Haynes, F.D., **Effect of temperature and strain rate on the strength of polycrystalline ice**, National Research Council, Canada, Associate Committee onGeotechnical Research, Technical Memorandum No. 121, October 1977, pp. 107-111, 8 refs.

The focus of this paper is on the results of laboratory tests on polycrystalline, isotropic snow ice. Test temperatures ranged from 0°C to -56°C, and strain rates ranged from 0.001/sec to 0.1/sec. Tests in both uniaxial compression and uniaxial tension were made on dumbbell-shaped specimens.

Hendrickson, G. and Rowland, R., **Strength studies on antarctic sea ice**, NTIS #AD-622 773, July 1965, 20 pp., 5 refs.

The strength of sea ice was studied at McMurdo, Antarctica, during two successive field seasons. Three hundred tensile tests were made on continuous core samples taken at various locations on ice aged 1 year, 2 years, and more than 5 years. Salinity profiles were obtained for each core. A relationship between strength volumes less than 0.400; strength equals 29.1 - 48.0 times the square root of the volume. The constants agree satisfactorily with values obtained previously for Arctic sea, the value for the strength of very low brine volume approaching the value for fresh-water ice. The model on which the above expression is based apparently breaks down at high brine volumes.

Hess, H., **On the elastic constants of ice**, NTIS #AD-881 102, 1950, 12 pp., 15 refs., *Translation from Zeitschrift fur Gletscherunke*, Vol. 27, 1940-41, pp. 1-19.

Data from earlier experiments were used to establish the dependency of Young's modulus on temperature and pressure within the range of 0-9°C. Functional relationships involving Poisson's ratio, the factor of incompressibility, the modulus of torsion, and Young's modulus were obtained. In measuring glacial depths with seismic waves, it was shown that in order to use appropriate velocity formulas, which are dependent on the above mentioned factors, a correction factor (between 1.5 and 3) must be applied to Young's modulus. Application of these formulas in connection with the seismic method yielded smaller depths for Greenland ice than had previously been found.

Higashi, A., **Plastic deformation of hollow ice cylinders under hydrostatic pressure**, NTIS #AD-233 534, July 1959, 10 pp., 10 refs.

The study was made in order to simulate the deformation of a tunnel in glacier ice and compare the results with the theoretical value derived from compression or tension tests. The plastic deformation of commercial polycrystalline ice and manufactured snow-ice was determined by measuring the discharge of oil from the cavity of closed hollow ice cylinders subjected to high external pressure in an oil-filled pressure chamber. The deformation vs time curves were similar to those obtained in compression or

tension tests. The relationships between minimum strain rate and applied pressure, or between minimum strain rate and the circumferential stress at the surface of the inner cavity, were found. Analysis of time-deformation curves indicates that viscoelastic models proposed by former investigators do not apply to the mechanism of the plastic deformation of ice.

Jellinek. H.H.G., **Tensile strength properties of ice adhering to stainless steel**, NTIS #AD-716 663, January 1957, 27 pp., 14 refs.

Tensile strength measurements on ice cylinders adhering to stainless steel have been made as a function of rate of loading, thickness, and cross-sectional area of specimens, and temperature. The experimental results are interpreted by means of a statistical treatment involving imperfections in the specimens. The statistics for a model consisting of a large number of parallel elements are elaborated on. The conclusion reached is that the tensile strength is a statistical function of the volume and cross-sectional area of the specimens due to imperfections. Superimposed on the statistical effect is a stress distribution effect, which becomes predominant for large volumes.

Kaplar, C.W., **Laboratory determination of dynamic moduli of frozen soils and of ice**, NTIS #AD-686 282, January 1969, 45 pp., Bibliog. pp. 24-27.

This report presents a summary of results of laboratory investigations of frozen soils and ice to determine the elastic moduli by the dynamic (sonic) method. The elastic moduli were indirectly obtained by measuring the fundamental resonant frequencies of flexural, longitudinal, and torsional vibrations induced in prismatic beams by electromagnetic means. Vibration tests were performed on a total of 56 specimens presenting 12 different materials. The dynamic moduli of elasticity of the frozen soils were found to increase with a decrease in temperature, the greatest rate of increase occurring between plus 32°F and plus 20°F. Coarse granular soils gave the highest values and clays the lowest in the ratio of more than 4 to 1. Dynamic Young's modulus, E, computed from flexural vibrations was usually lower than dynamic E computed from longitudinal vibrations. Average values of dynamic Poisson's ratio for all soil types computed from average values of E and G (longitudinal vibrations) ranged from 0.26 to 0.38. Dynamic moduli of ice E (longitudinal vibration) and G compared closely with values reported by other investigators.

Kerr, A.D., **Bearing capacity of floating ice plates subjected to static or quasi-static loads, a critical survey**, NTIS #ADA-009 363, April 1975, 43 pp., 157 refs.

This report contains a critical survey of the literature on the bearing capacity of floating ice plates. It consists of a discussion of general questions, a critical survey of analytical attempts to determine the bearing capacity of floating ice plates, and a survey of field and laboratory tests on floating ice plates and their relation to the analytical results. The paper concludes with a systematic summary of the results, a discussion of observed shortcomings, and suggestions for needed investigations.

Kerr, A.D., **Plastic deformation of floating ice plates subjected to static loads**, NTIS #AD-237 533, September 1959, 10 pp. plus 1p. appendix, 12 refs.

The problem is analyzed mathematically for decreasing and increasing rates of deflection. The analysis is based on the assumptions that for decreasing rates of deflection the floating ice plate will deform under lateral load without failure until the weight of the displaced water is equal to that of the load, and that for increasing rates, deflection increases until the ice plate collapses under and near the load. It is also suggested that the total deflection at a certain time is the result of the elastic deflection surface and the plastic deflection due to shear only, the shear forces obeying Newton's law of viscosity. Deflection equations for plastic deflection due to shear and derived for an infinite plate subjected to a line load, an infinite plate subjected to a concentrated force (axially symmetrical flexure), and an infinite plate subjected to uniform circular load. Equations for elastic deflection to be added to the plastic deflection due to shear are suggested. According to the statements and assumptions made and the results obtained, the total system of an ice plate resting on a liquid base can be considered as a Kelvin body for the case of decreasing rates of deflection.

Kerr, A.D., **Settlement and tilting of footings on a viscous foundation**, NTIS #AD-278 533, March 1962, 12 pp., 6 refs.

The concept of the Pasternak foundation, consisting of the Winkler foundation with shear interactions, is extended to the case of viscoelastic deformation, and the behavior of the foundation subjected to different types of load is studied as a function of time. The differential equation for the vertical surface displacements due to creep is formulated, and solutions for several loading cases are worked out. Two material parameters are also considered - a viscosity parameter related to the shear deformations and a visco-compressibility parameter of the vertical foundation elements. A procedure to determine these parameters is suggested, and the application of the analysis to the creep behavior of snow foundations is discussed.

Korzhavin, K.N., **Development of methods for determining ice pressure on bridge piers in the USSR**, Cold Regions Research and Engineering Lab, Hanover, New Hampshire, Report No. CRREL-TL347,

April 1972, 18 pp., Draft translation of Institut Inzhenerov Zheleznodorozhnogo Transporta, Novosibirsk. *Trudy* (USSR), No. 79, 1968, pp. 3-18.

Contents: Functioning of bridge piers during ice drift period; Extent to which problem has been studied; Evaluating the role of a structure's sloped edge; Evaluating the mechanical properties of ice during ice motion; Regioning of USSR territory according to strength of spring ice; Certain additional suggestions on allowing for the dynamic pressure of ice, included in instructions SN 76-66; Evaluating the effect of dynamic pressure of blocking and jamming masses on structures; the development of methods for determining the dynamic pressure of ice on bridge piers in the USSR.

Korzhavin K.N. and Ptukhin, F.I., **Evaluation of the compressive strength of ice under short-term rapidly increasing load**, Army Foreign Science and Technology Center, Washington, D.C., Report No. FSTC-HT-23-188-68, 21 August 1969, 18 pp., Translation of mono, Vsesoyuznaya Mezhduvedomstvennaya Soveshchaniya po Geokriologii (Merzlotovedemiyu) (8th). *Materialy*, Vol. 5, n.p. 1966, pp. 61-72.

A mathematical analysis of the strength of ice, as a component of frozen rock or soil. Strengths are differentiated for compressive and shear loading at various rates over various periods of time.

Lavrov, V.V., **The influence of ice structure upon its strength**, Arctic Institute of North America, Washington, D.C., January 1972, 16 pp., Draft translation of Problemy Arktiki i Antarktiki (USSR), Vol. 20, 1965, pp. 61-67.

The mechanical properties of ice depend upon the composition of the ice, and on its structure. The degree of this dependence, however, is unknown, since little research on this question has been done. The results of laboratory experiments conducted by the author are reported in the present article.

Michel, B., **Ice pressure on engineering structures**, NTIS #AD-709 625, June 1970, 71 pp., 79 refs.

This monograph summarized existing knowledge of forces exerted by an expanding ice sheet, impact forces of ice on structures, and vertical forces exerted by ice on hydraulic structures. Sections are also devoted to icebreakers and ice models.

Nakaya, U., **Visco-elastic properties of processed snow**, NTIS #AD-235 329, September 1959, 22 pp., 6 refs.

The results of investigations at Site 2 (Greenland) on rectangular samples of Peter snow (2 x 20 x 1.0 - 1.6 cm) of varying ages are reported, and the methods of study are described. Young's modulus was obtained from the frequency of resonance vibration and viscosity from the rate of damping, using a new visco-elastic meter. A simple relation was obtained between Young's modulus and density when the specimens were grouped according to structure, and the results of the experiments were analyzed for each of the groups, taking age as the parameter. Peter snow 2-3 yr old had almost the same modulus of elasticity as snow naturally compacted for 10 yr. The modulus of elasticity vs density curve for new Peter snow was similar to that of naturally compacted snow, except that the absolute value of the modulus of elasticity was smaller for the same density. Young's modulus, however, increased with time, and the curve approached that of naturally compacted snow. When the grain-size distribution was heterogeneous, Young's modulus was larger than for naturally compacted snow of the same density. Mechanical vibration immediately after processing effected an increase in snow density, but did not accelerate age hardening.

Nakaya, U., **Visco-elastic properties of snow and ice in the Greenland ice cap**, NTIS #AD-226 274, May 1959, 29 pp., 16 refs.

The results of studies in the summer of 1957 on ice samples taken from the ice tunnel at TUTO, core samples obtained by drilling in the ice cap at Site 2, and snow samples, using the transverse vibration method and a new portable meter, are reported. The modulus of elasticity of samples of density from 0.917-0.90 g/cu cm (tunnel ice) decreased sharply with slight deviations of the density from that of pure ice. At densities from 0.90-0.50 g/cu cm (deep-pit and drill-core samples) the relation between the modulus of elasticity and density was linear, while in the density range from 0.50-0.25 g/cu cm (surface snow) the modulus of elasticity decreased exponentially. The viscosity-density relation of the samples was similar to that of elasticity vs density. Young's modulus increases slightly with decreasing temperature, while viscosity increased exponentially. The activation energy was calculated as 18.7 kcal/mol for old ice-cap ice, 13.9 kcal/mol for tunnel ice with elongated bubbles, and 13.5 kcal/mol for superimposed ice.

Nevel, D.E., **Concentrated loads on plates**, NTIS #AD-703 876, March 1970, 8 pp., 11 refs.

An infinite plate on an elastic foundation is considered for a uniform load distributed over a circular area. The analysis of the problem is based on three-dimensional theory of elasticity. A numerical evaluation for the critical stress is made assuming a bending type of failure and the results closely agree with Westergaard's equations.

Nevel, D.E., **Ice bridge analysis**, NTIS #AD-615 736, April 1965, 10 pp.

A technique for strengthening of the ice on naturally frozen rivers is to successively flood and freeze within a confined width, creating a much thicker "ice bridge." An exact analysis is made of the elastic deformation and the movements in the bridge for arbitrarily placed,

concentrated, and distributed loads. The results are given in terms of infinite convergent series, which may easily be evaluated numerically. For the case of the infinitely wide river, the solutions become integrals.

Nevel, D.E., **Lifting forces exerted by ice on structures,** National Research Council, Canada, Associate Committee on Geotechnical Research, Technical Memorandum No. 92, March 1968, and proceeding of a conference held at Laval University, Quebec, 10-11 November 1966, pp. 155-161, 6 refs.

If a floating ice sheet is connected to a structure when the water level is increased, the ice sheet will be bent and a lifting force will be exerted on the structure. In this paper, cylindrical bending of the ice sheet is considered as a homogeneous isotropic plate resting on an elastic foundation of the Winkler type. The deflections and thickness of the plate will be assumed to be small. The ice is considered as a linear viscoelastic material that has an indefinite bulk modulus and a shear mode that obeys a Maxwell model. A solution is given of the problem when the rise in water level is composed of a linear combination of ramp functions of time, which can be made to approximate any function. In order to easily determine the long time effects, the ice is considered viscous under shear. For this case solutions are given when the change of water level is a ramp function, a step function, and a sine function. In addition to the above subject, a brief note is presented on thermal stresses in a floating ice sheet when the ice is considered viscoelastic.

Nevel, D.E., **A semi-infinite plate on an elastic foundation**, NTIS #AD-616 313, March 1965, 12 pp. plus 2 pp. appendix, 7 refs.

The solution of the problem of semi-infinite plate on an elastic foundation is presented. This problem occurs when a load is applied near the edge of a floating ice sheet. The equations are evaluated for an edge load, and the results are given in graphical form for the following: (a) the maximum deflection that occurs at the edge under the load, (b) the movement that causes the initial cracking of the plate, (c) the distance from the edge that the circumferential crack will occur, and (d) the moment that causes the circumferential crack. The same method of solution can be applied to an infinite strip on an elastic foundation with any combination of simple, rigid, or free support at the edges.

Nevel, D.E., **Vibration of a floating ice sheet**, NTIS #AD-712 995, August 1970, 8 pp., 2 refs.

The solution for the vibration of an elastic plate floating on water is developed. The water is assumed to be incompressible and to have irrotational flow. In free vibration upon release of the plate, the maximum negative rebound of the deflection is 25 percent. For forced vibration, the steady state part of the solution shows that there is a frequency at which the deflection is a maximum. The stresses become a maximum at a frequency higher than the one for deflection. These critical frequencies depend upon the plate's characteristic length and the depth of the water. For most situations the critical frequency for a stress is less than 0.2 cycles/second. At this critical frequency the stresses are amplified over the static case by a factor less than 10 percent.

Parameswaran, V.R., **Work-hardening and strain rate sensitivity of flow stress in high purity ice single crystals**, NTIS #ADA-018 015, October 1975, 11 pp., 16 refs.

Single crystals of high purity ice deformed by uniaxial compression on an Instron machine showed remarkable work-hardening after about 8% strain. By changing the strain rate during compression tests in the plastic region of the stress-strain curve, an apparent activation volume $V^*$ and a dislocation mobility exponent m were calculated from the strain rate sensitivity of flow stress. The large work-hardening and the rapid increase in the value of m beyond about 10% strain indicate that the plastic flow in this region is controlled by dislocation of intersections and nonconservative motion of jogs.

Perham, R.E., **St. Mary's River ice booms: design force estimate and field measurements**, NTIS #ADA-037 092, February 1977, 26 pp., 13 ref.

A set of two ice booms with a 250-ft (76m)-wide navigation opening between them was designed to stabilize the ice cover in the harbor in Sault Ste. Marie, Michigan and Ontario, and to reduce the ice losses associated with winter navigation of ships on the St. Mary's River. The forces from natural effects on the ice cover were predicted using existing theory and physical data for the area. The forces in the boom structure resulting from ice cover and boom interaction were estimated. When the ice booms were installed, force measurement systems were put into selected anchor cables. These systems were operated all winter in conjunction with a modest program of supplemental data gathering. The force data exhibited periods when the force distribution was in good agreement with predictions and periods when the effect of ice on the booms differed substantially from predictions. Sometimes passing ships had a substantial effect on the ice cover and the boom loads, and at other times, the effect was negligible. The direction of travel made little difference on average peak loads. The maximum loads on the booms resulted from natural occurrences.

Shapiro, G.S., **Deflection of a semi-infinite plate on an elastic foundation,** NTIS #AD-070 155, January 1955, 9 pp., 7 refs., Translation from *Prikldanaia matematika i mekhanika*, Vol. 7, 1943.

The mechanics of a floating ice sheet subject to the action of a load near or on an edge or a crack is one of

the basic problems in the bearing capacity of ice. The paper studies the problem of an infinite strip plate under the action of a point load using the Westergaard-Gersanov method, but applying Fourier integral instead of series. Results of computations for a plate loaded by a concentrated force on the edge, for a uniformly distributed load on a part of the edge, and uniformly distributed load on a line perpendicular to the edge, are given.

Smith, N., **Determining the dynamic properties of snow and ice by forced vibration**, NTIS #AD-694 376, June 1969, 17 pp., 6 refs.

The complex dynamic Young's and shear moduli, loss factor, and Poisson's ratio are presented for naturally compacted glacial snow through a density range of 0.4 to 0.9 g/cu cm. A frequency dependence of the moduli and its effect on the computation of Poisson's ratio is demonstrated. Considerable scatter is exhibited in the loss factor measurements; however, indications are that the loss factors have negligible effect on the modulus computations.

Weeks, W.F., **Studies of salt ice I: the tensile strength of NaCl ice**, NTIS #AD-277 540, August 1961, 30 pp. plus 23 pp. appends., 26 refs.

Ice samples from fresh water and at salinities ranging from 1 - 22 per mill were prepared in a tank designed to simulate the one-dimensional cooling of natural water bodies. Phase and density relations were computed for these salinities in the temperature range 0 to -35°C and a determination made of the dependence of ring-tensile strength of the ice samples on temperature, brine volume, NaCl.2(H20) volume, and thermal history. The results indicate that the strength of fresh water ice is essentially temperature independent in the temperature range -10 to -30°C; the strength of ice containing crystals of NaCl.2(H20) is essentially independent of the temperature of the sample and the volume of NaCl.2(H20) in the ice. The strength of salt ice at temperatures between -5°C and the eutectic point (1-21.2°C) decreases with an increase in the volume of brine in the ice and can be considered a unique function of the brine volume, independent of the individual temperature and salinity values. It is suggested that the strength of fresh water ice should be considered as a limit that is approached but not exceeded by salt ice.

Wilson, J.T., **Coupling between moving loads and flexural waves in floating ice sheets**, NTIS #AD-099 494, September 1955, 28 pp., 7 refs.

The elementary theory of coupling of resonance between a moving load and the flexural waves generated by it in a floating ice sheet is developed and verified by experiments. The theory indicates that for shallow water the critical velocity is approximately 20 percent greater than the velocity of long water waves. Experiments were carried out using one and two vehicles as moving loads on ice sheets one to two feet thick. At the critical speed (for a single vehicle) the maximum observed motion was approximately 2.5 times the static deflection. For two vehicles running in tandem a half wave length apart, a considerable cancellation was observed. Attempts to solve the problem of a semi-infinite plate on an elastic foundation with a free edge under concentrated load (the ice-breaker problem) are reported. No satisfactory solution was obtained.

Ziegler, H., **Methods of the theory of plasticity in the mechanics of snow**, NTIS #AD-877 348, Hanover, New Hampshire, CRREL, 1970, 30 pp., Translation of **Methoden der Plastizitatstheorie in der Schneemechanik**, *Zeitschrift fur angewandte Mathematik and Physik*, Vol. 14, No. 6, 1963, pp.713-737, 12 refs.

It seems reasonable to assume that, in certain problems, some types of snow may be considered perfect plastic bodies. With this assumption, various problems concerned with the formation of avalanches and with its prevention are discussed.

## E. General Physical Properties

Abrams, W.R. and Frankenstein, G.E., **Acoustic reflection measurements of sea ice thickness, Barrow, Alaska**, Defence Research Board, Defence Research Establishment, Ottawa, Technical Note No. 71-14, June 1971, pp. 29-41.

The sea ice thickness was more readily determined when using the 12 kHz system than the 3.5-kHz system. This followed from the better resolution inherent in the use of higher frequencies. There is a strong indication that the use of frequencies higher than 12 kHz will provide a useful operational tool for rapid determination of sea ice thickness.

Ackley, S.F. and Keliher, T.E., **Comparison between derived internal dielectric properties and radio-echo sounding records of the ice sheet at Cape Folger, Antarctica**, NTIS #ADA-055 245, April 1978, 12 pp., 17 refs.

The use of radio-echo sounding records to indicate the presence of internal layers within large ice sheets is of interest to glaciologists because it offers a means of tracking the internal properties of the ice sheets over large distances. The interpretation of the reflections obtained in this manner is more valuable, however, if a physical property change relating to the glaciological regime can be related to the dielectric property change producing the radio-echo reflections. In this report, we use the measured physical properties of core to bedrock taken at Cape Folger, East Antarctica, to compute a profile for comparison with the observed radio-echo reflections. The measurements available on physical properties are: density variations, bubble size and shape changes, and crystal fabric variations. The depths of the strong reflections shown on the available radio-echo records are in reasonable agreement with the depths corresponding to the highest reflection coefficients computed from the combined physical property measurements. In calculations to differentiate the separate effects of different physical properties, it appears that density variations account for the primary contributions to the calculated dielectric property changes corresponding to the highest reflection coefficients. However, bubble changes alone can also account for reasonable, though lower, reflection coefficients at the appropriate depths. Crystal fabric variations correspond poorly with the reflection locations. Density variations are normally associated with depositional events in the history of the ice sheet. However, the close correspondence between the depths of the bubble shape changes (which are definitely deformational features), and the depths of the density variations, and between both of these and the radio-echo layers, indicate that deformational events in the ice sheet's history are represented by the variations in the physical property and associated radio-echo records.

Ackley, S.F., Hibler, W.D., III, Kovacs, A., Kuqzruk, F.K., and Weeks, W.F., **Thickness and roughness variations of arctic multiyear sea ice**, NTIS #ADA-028 086, June 1976, 25 pp., 11 refs.

Three surface elevation and ice thickness profiles obtained during the 1972 Arctic Ice Dynamics Joint Experiment Pilot Study on a multiyear ice flow were analyzed to obtain relationships between the surface elevation, thickness, and physical properties of the ice. It was found that for ice freeboards from 0.10 m to 1.05 m above sea level a linear relationship between the ice density and the freeboard could be postulated in a statistical relationship consistent with the observed physical properties, which indicate that as the ice freeboard increases, the ice salinity decreases and the higher freeboard or thicker ice therefore decreases in density. Using this variable density with freeboard relationship, a model was constructed to predict the ice thickness, given the ice freeboard and snow depth alone. The model was compared with two other models, one assuming constant ice density (independent of freeboard) and the other using smooth filters for predicting the ice thickness. It was found that the variable density prediction model gave the best approximation to the observed ice thickness, with a standard error between the measured and predicted value of about 0.4 m, compared with errors from 50 to 100% higher for the other two models. The model was also compared with data on multiyear ice from two other investigations in different regions and was found to give error estimates similar to the error of the data set on which the model was based. It is therefore concluded that the model can be useful to estimate multiyear ice thicknesses from surface elevation formation obtained either by ground-based techniques or by aerial methods such as laser profilometry or stereo aerial photogrammetry. The effect of the variable density on estimates of the stress induced loading was examined and the results are presented in this appendix. Consideration of this property led to the conclusion that stresses from sources other than isostatic imbalance must account for 75% or more of the bending stresses necessary to induce cracking in multiyear ice.

Anderson, D.M. and Banin, A., **Effects of salt concentration changes during freezing on the unfrozen water content of porous materials**, *Water Resources Research*, Vol. 10, No. 1, February 1974, pp. 124-127, 12 refs.

By combining equations for salt concentration by water removal from porous bodies with those for freezing point depression in normal solutions, equations are developed for calculating freezing point depression shifts due to the gradual removal of water upon freezing in porous bodies. The same equations can be used for the calculation of shifts in the osmotic potential of water in drying porous bodies by using a simple conversion factor. Graphs relating the remaining water content to the freezing poing shift for var-

ious initial soluble salt contents are given. Good agreement is found between the measured freezing point depression shifts for a silty clay soil treated with three concentrations of sodium chloride and with dimethyl sulfoxide at various contents of unfrozen water and the calculated values. The order of magnitude of the shifts expected in various natural conditions is discussed.

Arnold, D.A., Camp, P.R., and Kiszenick, W., **Electrical conduction of ice**, 1965, 64 pp., Unpublished manuscript, No microfiche available.

This article pertains to ice electrical properties, ice resistivity, electrical resistivity, and conduction.

Ashton, G.D. and Calkins, D.J., **Arching of fragmented ice covers**, *Canadian Journal of Civil Engineering*, Vol. 2, No. 4, December 1975, pp. 392-399, 2 refs., In English with French summary, For another version see CRREL #29-4015.

Among the problems associated with the extension of the winter navigation season on the Great Lakes and the St. Lawrence River, the obstruction of navigation posed by a continuous ice boom across a water body may possibly be solved by creating a gap or opening in the boom, through which vessels may pass, but which will promote retention of floating ice pieces by arching. A laboratory study of arching by fragmented ice floes across a gap in a surface obstacle was conducted in a 0.9 m wide hydraulic flume using simulated ice floes. Polyethylene blocks, 37 mm and 74 mm square by 6.4 mm thick, were used in both single-sized runs and combination-sized runs. The simulated ice nonoccurrence of a stable arch was observed and recorded by time-lapse photography. In a corollary series of experiments an arch, once formed, was subjected to a disturbance simulating the passage of a vessel through the ice field. The area of ice floes released as a result of the disturbance before arching reoccurred was found to be, on average, equivalent to the square of the gap width.

Ashton, G.D. and Kennedy, J.F., **Ripples on underside of river ice covers**, *Journal of the American Society of Civil Engineers, Hydraulics Division*, Vol. 98, No HY9, September 1972, pp. 1603-1624, 14 refs.

A mathematical model is developed to predict the occurrence and describe the properties and behavior of ice ripples that form on the underside of river ice-covers. The local rate of freezing or melting at the ice-flow interface is related to the difference between the local heat transfer rates by conduction through the ice and by turbulent transfer from the flow to the ice. The local heat flux to the interface from the flow is expressed as a small perturbation expansion in terms of the steepness of the monochromatic interfacial wave, and is assumed to be shifted relative to the interface wave. The analysis yields a stability criterion and expressions for the amplification rate and celerity of the ripples. Laboratory data are used to obtain values for the constants introduced into the theory and to corroborate the analytical results. Field data are examined in the light of the laboratory results.

Assur, A., **Antarctic sea ice**, International Association of Scientific Hydrology, Publication No. 86, 1970, p. 543, abstract only.

This article pertains to sea ice, salinity, tensile strength, and flexural strength.

Assur, A., **Correction for bromide during chloride titration of sea-ice brine**, NTIS #AD-653 133, January 1960, 4 pp., 4 refs.

An explanation is given to account for the effect of bromide on the chlorinity of sea water brine; the resultant is termed chloride equivalent. In many cases the correction for bromide will not be significant but should be included in striving for greatest accuracy in the chemical analysis of sea water.

Assur, A. and Weeks, W.F., **Growth, structure, and strength of sea ice**, NTIS #AD-450 186, October 1964, 19 pp., 26 refs.

The freezing interface determines the basic characteristics of salt ice. As the platelets composing the individual crystals of salt-ice grow, impurities such as salt are rejected by the ice crystals and diffuse away from the platelets. The freezing point is lowered within the diffusion cloud preventing other platelets from growing in the vicinity. As a result, the plate spacing decreases with increasing growth rate, The physical constants involved are the diffusion coefficient of salt in water, and the roughness of the freezing interface. Several solutions to the problem of developing a general relation using only physical parameters are considered. The strength of sea ice is shown to depend upon past weather history. The relations allow the determination of sea-ice strength and explain observed discrepancies between properties of sea ice in various geographical areas.

Assur, A. and Weeks, W.F., **Structural control of the vertical variation of the strength of sea and salt ice**, NTIS #AD-602 458, April 1964, 16 pp., 18 refs.

The vertical variation in the strength of sea ice was studied by using data from NaCl ice, which shows a structural similarity to sea ice and has straightforward phase relations. Nested horizontal thin sections were prepared at seven different levels below the surface of the test NaCl ice sheet and the plate spacing and the distance between centers of adjacent brine layers measured parallel to the c-crystallographic axis were determined. The measurements show that the plate spacing is a linear function of the sixth root of the distance below the upper ice surface (z). Available values of the same parameter for natural sea ice are in good agreement with this relation. Equations giving

the dependence of the ring-tensile strength of the ice on z are developed. It is demonstrated that in NaCl ice sheets the systematic increase of the plate width with depth produces significant changes in the ring-tensile strength of the ice. Field tests previously performed indicate that similar relations hold for sea ice.

Bader,H., **Density of ice as a function of temperature and stress**, NTIS #AD-448 069, August 1964, 6 pp., 5 refs.

The equations for calculating the density of ice of moderate porosity (density more than 0.8) as a function of temperature and stress condition are calculated from the best available experimental data.

Bender, J.A., **Snow and ice**, *American Geophysical Union, Transactions*, Vol. 48, No. 2, June 1967, pp. 724-729.

A brief review of the literature on snow hydrology and the properties of ice is presented, along with a bibliography.

Berkovich, E.S. and Krushchov, N.N., **Study of the hardness of ice**, NTIS #AD-716 457, 1970, 48 pp., 25 refs., Translation of Izuchenie tverdosti l'da. Moscow, Izdo AN SSSR, 1960.

The present monograph is intended as a systematic representation of data collected on the hardness of ice by the present author and other investigators using various methods. It is believed that the monograph will be of general interest to scientists and engineering-technical workers concerned in any way with ice, frozen soil, or snow at low temperatures.

Brill, R. and Camp, P.R., **Properties of ice**, NTIS #AD-277 536, May 1961, 75 pp. plus 2 pp. appendix, 34 refs.

This report summarizes the results of a number of studies on ice performed by researchers at the Polytechnic Institute of Brooklyn during the period 1955-1959. Sections of the report are entitled as follows: growth of large single crystals of ice and ammonium-fluoride ice; lattice constants of mixed crystals of ice and ammoniumfluoride; degree of perfection of glacial ice crystals; thermal motion in ice and heavy ice; viscoelastic properties of ice; diffusion of ammonium-fluoride through ice; dielectric relaxation; effect of pressure on dielectric relaxation; effect of pressure on dielectric properties; and investigation of the polarity of ice crystals.

Brill, R., **Structure of ice**, NTIS #AD-149, 029, July 1957, 67 pp.

The procedures for growing samples of ice used in the experiments are described. Experiments using the method of bending bars of ice to determine their viscoelastic behavior were made. Tests were conducted on single crystals with various orientations, polycrystalline samples, and mixed crystals of ice-NH4F. These tests showed that the hexagonal base plane is the gliding plane at plastic deformation and that Becker's equation can be used for description of the viscoelastic creep of ice. Studies show that amounts up to 10 percent of NH4F may be absorbed in the ice lattice. Dielectric studies indicate that the relaxation time decreases markedly with increasing concentration of NH4F, down to a minimum value corresponding to some concentration between 0.1 and 1 per cent NH4F, and then increases again with further increasing concentration. The dc resistivity of ice-NH4F increased with the x-ray diffraction technique to determine the thermal amplitudes of $H_2O$ molecules as well as of hydrogen atoms in ice. The molecular vibration can be described as having a characteristic temperature of 220°K.

Butkovich, T.R., **Linear thermal expansion of ice**, NTIS #AD-158 192, December 1957, 10 pp., 8 refs.

Experiments were conducted on natural and artificial single ice crystals, commerical ice, snow-ice, and a glacial single crystal at temperatures from 0°C to -30°C to determine the effect of orientation on the linear thermal expansion coefficients. The orientation of the c-axis, the type of ice (whether single or polycrystalline), and the grain size did not appreciably affect the values of the coefficient; ice was practically isotropic with respect to thermal expansion at the temperatures tested. There was a steady decrease of the expansion coefficient with each succeeding measurement on the same specimen, a phenomenon attributable to slow annealing. The ratio of the specific heat at constant pressure to that at constant volume averaged 1.030 from 0°C to -30°C. Gruneisen's constant was found to be about 0.78 and independent of temperature. An equation expressing the average coefficient of linear thermal expansion of ice of any type or orientation is presented.

Camp, P.R., **Properties of ice, Part II**, NTIS #AD-600 883, November 1963, 38 pp., 19 refs., For Part I see CRREL #24-3226.

Modifications are reported of a previously described apparatus for the preparation of single crystals of pure and doped ice. Some results of using this apparatus to grow crystals of several crystallographic orientations are discussed. An effect of an electric field on the nucleation of ice at a metal-water interface is described. Various x-ray techiques for investigating the quality of ice crystals are discussed and experimental results of applying them to Alaskan Glacier crystals are given. Dielectric relaxation and electrical conductivity of ice are discussed. Experiments have been performed to determine the effect of length of the sample and to study the effect of small amounts of NH4F as a substitutional impurity. Special attention is given to long period dielectric processes. At least two such processes seem to be present, one which dominates the first 3 to 30 seconds of discharge and the

other which determines the long time behavior. The possibility of altering the conductivity and dielectric relaxation of ice by optical generations of Bjerrum defects is explored and experiments to test this possibility are reported.

Capillino, P. and Hoekstra, P., **Dielectric properties of sea and sodium chloride ice at UHF and microwave frequencies**, *Journal of Geophysical Research*, Vol. 76, No. 20, 10 July 1971, pp. 4922-4931, 20 refs.

Sea ice differs from fresh water ice in physical behavior because of the entrapment of liquid inclusions of brine in the ice matrix. This difference is strongly evident in the dielectric properties of the two ice forms. The liquid inclusions in sea ice cause sea ice to be a lossy dielectric at microwave frequencies. The dielectric loss of sea ice at microwave frequencies is caused by two mechanisms, ionic conductivities and dipole rotations of the water molecules. The complex dielectric constant of sea ice was determined in various frequency ranges by measuring the changes in phase and amplitude when samples were placed in coaxial lines and waveguides. The measured values of the dielectric loss agree well with computations made using low-frequency conductivity, brine volume, and salinity as known parameters.

Coon, M.D., **Mechanical behavior of compacted arctic ice flows**, *Journal of Petroleum Technology*, Vol. 26, 1974, pp. 466-470.

Small blocks of ice, broken in a bending mode off large floes, are assumed to behave like granular media except in states of compression, where single blocks may buckle, leading to ridging and rafting. This sequence of events leads rationally to a failure law and flow rule that can be used in analyzing the stress of arctic sea ice.

Cox, G.F.N. and Weeks, W.F., **Brine drainage and initial salt entrapment in sodium chloride ice**, NTIS #ADA-021 765, December 1975, 85 pp., 41 refs.

Using radioactive 22Na as a tracer, it was possible to determine both the concentration and movement of the brine within the ice without destroying the sample. A detailed temperature and growth history of the ice was also maintained so that the variation of the salinity profiles could be properly interpreted. In all respects, the salinity profiles are similar to those of natural sea ice. They have characteristic C-shape, and clearly exhibit the effects of brine drainage. To determine the relative importance of the desalination mechanisms, a theoretical brine expulsion model was derived and compared to the experimental data. As input for the model, equations describing the variation of some properties of NaCl brine with temperature were derived. These included the brine salinity, viscosity, specific heat, thermal conductivity, and latent heat of freezing. The theoretical brine expulsion model was derived by performing mass and energy balances over a control volume of NaCl ice. A simplified form of the model, when compared to the experimental results, indicated that brine expulsion was only important during the first several hours of ice growth, and later became a minor desalination process relative to gravity drainage, which continued to be the dominant mechanism for the remainder of the study period (up to 6 weeks). The rate of gravity drainage was found to be dependent on the brine volume and the temperature gradient of the ice. As either the brine volume or temperature gradient was increased, the rate of change of salinity due to gravity drainage increased. The equation commonly used to calculate the effective distribution coefficient (Weeks and Lofgren, 1967) was modified and improved by taking brine drainage into account. An expression was also derived to give the distribution coefficient at very low growth velocities.

Cox, G.F.N. and Weeks, W.F., **Laboratory preparation of artificial sea and salt ice**, NTIS #AD-780 694, June 1974, 15 pp.

The characteristics of several successful schemes that have been used to produce artificial sea and salt ice for laboratory studies are discussed. Difficulties that have been encountered in developing suitable experimental designs for investigating a variety of specific sea ice problems (salinity, grain size, substructure and orientation variation, preparation of single crystals, and underwater ice) are discussed and suggestions are given for improved methods.

Cox, G.F.N. and Weeks, W.F., **Salinity variations in sea ice**, *Journal of Glaciology*, Vol. 13, No. 67, 1974, pp. 109-122, 3 refs., In English with French and German summaries.

The salinity distribution in multi-year sea ice is dependent on the ice topography and cannot be adequately represented by a single average profile. The cores collected from areas beneath surface hummocks generally showed a systematic increase in salinity with depth from 0 per mille at the surface to about 4 per mille at the base. The cores collected from areas beneath surface depressions were much more saline and displayed large salinity fluctuations. Salinity observations from sea ice of varying thicknesses and ages collected at various arctic and sub-antarctic locations revealed a strong correlation between the average salinity of the ice, S, and the ice thickness, h. For salinity samples collected from cold sea ice at the end of the growth season, this relationship can be represented by two linear equations: $S = 14.24 - 19.39\,h$ ($h < 0.4$ m); $S = 7.88 - 1.59\,h$ ($h > 0.4$ m). It is suggested that the pronounced break in slope at 0.4 m is due to a change in the dominant brine drainage mechanism from brine expulsion to gravity drainage. A linear regression for the data collected during the melt sea-

son gives S = 1.58 + 0.18 h. An annual cyclic variation of the mean salinity exists for multi-year sea ice. The mean salinity reaches a maximum at the end of the growth season and a minimum at the end of the melt season.

Dixit, B. and Pounder, E.R., **Specific heat of saline ice**, *Journal of Glaciology*, Vol. 14, No. 71, 1975, pp. 459-465, In English with French and German summaries.

A calorimetric experiment was performed to determine empirically the dependence of the specific heat of ice with salinity 0-10% over the temperature range from -23°C to the melting point. The experimental results agree with the theoretical model determined by Schwerdtfeger (1963) for calculating the specific heat, except within several degrees of the melting point and for very pure ice.

Dunkle, R.V. and Gier, J.T., **Radiation in a diffusing medium with application to snow**, NTIS #AD-023 217, November 1953, 14 pp., 3 refs.

The transmission through an idealized snow cover has been shown to be directly related to the albedo and be an exponentially decreasing function. Two parameters have been proposed as possible correlating factors for transmission and albedo measurements. The first factor is a characteristic of the surface condition of the cover; the second is a characteristic of the snow beneath the surface.

Epstein, S. and Gow, A.J., **On the use of stable isotopes to trace the origins of ice in a floating ice tongue**, *Journal of Geophysical Research*, Vol. 77, No. 33, Nov. 20, pp. 6552-6557, 20 refs.

Stable isotope analysis has been used successfully to distinguish between several different ice types in an ice tongue floating on sea water in Antarctica. At one critical location this technique has provided the only means of discriminating unambiguously between glacial ice and fresh-water ice formed from desalinated sea water. This part of the ice tongue is now underlain by a layer of desalted sea water thick enough to prevent any further accretion of sea ice at this location.

Frankenstein, G.E., **Equations for determining the brine volume of sea ice from -0.5 to -22.9°C**, *Journal of Glaciology*, Vol. 6, No. 48, October 1967, pp. 943-944, 1 ref., In English with French and German summaries.

Brine volume of sea ice is a function of the salinity and temperature of the ice, and it is related to its strength. This paper gives three equations that can be used to compute the brine volume for three temperature ranges from -0.5 to -22.9°C. A less accurate equation covering the total range is also presented.

Frankenstein, G.E., **Flexural strength of sea ice as determined from salinity and temperature profiles**, National Research Council, Canada, Associate Committee on Geotechnical Research, Technical Memorandum No. 98, November 1970, pp. 66-73, 7 refs.

The paper discusses the results of large in-place cantilever beam tests on sea ice whose strength values were used to compute the constant of the strength of the equation based on profile relationship. Profile relationships are based on change in brine volume.

Fujino, K., **Dielectric properties of sea ice**, NTIS #AD-877 403, 1970, 54 pp., 30 refs., For original Japanese article see CRREL #23-2752.

Temperature characteristics and frequency characteristics of dielectric properties of natural sea ice gained by measurement may be summarized as follows. Corresponding to changes in volume and composition of brine due to temperature and the precipitation point and the eutectic point at which liquid brine solidifies, discontinuous changes are manifested. Frequency characteristic curves with temperature as a parameter are divided into three groups corresponding to those temperatures. The frequency characteristic in the temperature range above the eutetic point where liquid brine exists manifests a notably different characteristic than the temperature range below it. It can be inferred that in the temperature range above the eutectic point, structural dispersions on the surface of ice and liquid brine (which is an electrolytic solution) is dominant, and that in the temperature range below that where liquid brine does not exist, the contribution of electrolytic brine disappears and molecular dispersion of ice molecules themselves becomes dominant.

Glen, J.W., **Mechanics of ice**, NTIS #ADA-022 797, December 1975, 43 pp., 134 refs.

This monograph summarized knowledge of the mechanics of ice to 1970. It is concerned principally with the effect of stress on the mechanical properties of ice, including elasticity, anelasticity, sound propagation, plastic deformation and creep in single crystals and in polycrystalline ice, fracture, and recrystallization and grain growth that accompanies plastic deformation. The monograph also includes a comprehensive bibliography.

Glen, J.W., **Physics of ice**, NTIS #AD-778 009, April 1974, 81 pp.

Existing knowledge of ice physics is summarized. Ice crystalline structure including defects in structure, polycrystalline ice and grain boundaries, electrical properties, thermal properties, propagation of electromagnetic waves in ice and optical properties, nucleation and growth of ice cyrstals, melting and evaporation, and surface properties are covered. A comprehensive bibliography is given.

Gow, A.J. and Kovacs, A., **Dielectric constant and reflection coefficient of the snow surface and near-surface internal layers in the McMurdo Ice Shelf**, *Antarctic Journal of the United States*, Vol. 12, No. 4, October 1977, pp. 137-138, 9 refs.

An impulse radar system was used to profile the shape and lateral extent of the brine layer in the McMurdo Ice Shelf. A small antenna was also used to determine if reflective layers could be detected in the upper 5 m of snow. The radiated impulse center frequency was 626 megahertz with an estimated frequency spectrum of 375 and 875 at the -3 decibel points. The measurements technique is described. The study indicates that layers of dielectric discontinuity can be detected at shallow depths in polar snow. The shallow depth at which the internal layers were detected suggests that they represent density variations in the snow, perhaps associated with summer melt features less than 5 mm thick.

Gow, A.J. and Sheehy, W., **Effect of porosity on the hydrostatic compression of ice**, NTIS #ADA-017 302, October 1975, 9 pp., 4 refs.

A cathetometer was used in conjunction with a window-equipped pressure chamber to measure linear deformation in porous polycrystalline ice samples compressed hydrostatically at pressures of up to 0.31 kb. Tests show that porosity as little as 1% can increase the compressibility of ice four- or fivefold. However, the compression is of a substantially non-elastic nature, since very little recovery (expansion) occurs during and following pressure release. Pore closure, which is virtually complete at the higher pressures, can be attributed to a combination of plastic and cataclastic deformation of ice in the walls of the pores.

Gow, A.J. and Langston, D., **Growth history of lake ice in relation to its stratigraphic, crystalline, and mechanical structure**, NTIS #ADA-036 228, January 1977, 24 pp., 9 refs.

Studies of the growth history and structural characteristics of winter ice covers on two New Hampshire lakes are described. These investigations included measurements of ice cover thickness, characterization of the stratigraphic and crystalline structure of the ice, identifiation and classification of major ice types, and measurements of electrolytic conductivity. The formation of cracks and flaws in the ice and their effects on the mechanical properties of the ice were also investigated. A method of correlating ice growth with surface wind and temperature measurement is described and the interrelationships of the various physical and mechanical properties of temperate lake ice covers are discussed.

Gow, A.J. and Williamson, T.C., **Linear compressibility of ice**, *Journal of Geophysical Research*, Vol. 77, No. 3, 10 November 1972, pp. 6348-6352, 7 refs.

A novel technique of measuring the linear compressibility of ice at relatively low pressures (less than 0.5 kb) is described. A cathetometer was used in conjunction with a window-equipped pressure chamber to measure changes in the lengths of ice specimens compressed hydrostatically to 0.31kb. A mean linear compressibility of 3.7mb exp -1 was obtained at -10°C, and the compressibilities perpendicular and parallel to the c-axis of single crystals of ice were found to agree within 10 percent.

Gow, A.J. and Weeks, W.F., **Preferred crystal orientations in the fast ice along the margins of the Arctic Ocean**, *Journal of Geophysical Research*, Vol. 83, No. 10, October 20, 1978, pp. 5105-5121.

Field observations of the growth fabrics of the fast and near-fast ice along the coasts of the Beaufort and Chukchi seas show that at depths K60 cm below the upper ice surface the sea ice crystals show striking alignments within the horizontal plane. At one site this alignment was well developed at a depth of 15 cm, and in all cases the degree of preferred orientation increased with depth. In general, the c-axes of the crystals were aligned roughly E-W parallel to the coast. In the vicinity of islands, alignment roughly paralleled the outlines of the islands, and in narrow passes between islands the alignment paralleled the channel. It should be assumed that the c axes of the crystals were aligned parallel to the "long-term" current direction at the sea ice-seawater interface. The alignments are apparently the result of geometric selection among the growing crystals, the most favored orientation being that in which the current flows normal to the (0001) plates of ice that make up the dendritic ice/-water interface characteristic of sea ice. Current flow in this direction reduces the thickness of the solute boundary layer as well as the salinity in the liquid at the interface. This lowered salinity allows crystals in the favored orientation to extend farther into the melt than neighboring crystals with less favored orientations. In addition, the current ends to induce a continuous flux of supercooled seawater against the sides of the crystals that extend ahead of the interface. This favors their lateral growth. The aligned crystal aggregate that forms has the overall characteristics of a single crystal. The development of such crystal alignments results in pronounced anisotropy in the mechanical, thermal, and electrical properties of fast ice. It is suggested that such crystal orientations can be used as an aid in determining current patterns in perennially ice-covered areas such as the Canadian Archipelago.

Granicher, H. and Jona, F., **Physics of ice**, Arctic Institute of North America, January 1972, 16 pp.

The report reviews research of ice on hydrogen bonds; oxygen atoms in the ice lattice; electrical properties; dielectric properties; space charge effects;

conductivity; and elastic properties of ice crystals.

Grinblat, S.B., **Porous alabaster and snow concrete**, NTIS #AD-711 872, 1970, 3 pp., Translation of **I Acheistyi alebastr i snegotsementynyi kamen'**, *Promyshlennoe stroitel'stvo*, Vol. 19, No. 7-8, 1941, p. 39.

Ice and snow alabaster is obtained by mixing alabaster with snow and water, and after 10-15 minutes the member is strong enough to be carried into the drying room. In this way, a material with much better properties than foam alabaster can be obtained from alabaster without wasting valuable products in preparing a foaming emulsion. Similarly, it is possible to obtain a foam concrete that can be used as load-bearing members, ceilings, etc.

Hallikainen, M., **Dielectric properties of sea ice at microwave frequencies**, Helsinki University of Technology, Espoo, Finland, Radio Laboratory, Report No. REPT-S-94 ISBN-951-750-960-X, 1977, 55 pp.

The dielectric properties of fresh water ice at microwave frequencies are reviewed. The properties of brine liquid were approximated by those of aqueous NaCl solutions. Various models for the shape and geometrical arrangement of brine pockets were used to obtain the dielectric properties of the mixture as a function of frequency, temperature, and salinity. The method can be applied at microwave frequencies when the length of brine inclusions is much smaller than the wavelength. The equations used for obtaining the properties of liquid brine are valid only at temperatures close to the freezing point of sea water. In Finland the temperature of ice is generally higher than -5°C so that the temperature range of calculations is adequate in most cases. The temperature dependence of the theoretical results agrees fairly well with the experimental values reported in literature. The model that assumes that brine pockets are elongated ellipsoids, the orientation of which is random, gives results that best agree with measurements.

Hamilton, W.L. and Weeks, W.F., **Petrographic characteristics of young sea ice, Point Barrow, Alaska**, NTIS #AD-294 162, October 1962, 11 pp., 17 refs.

Horizontal thin sections under low magnification of a 31.4 cm-long sea ice core were examined. Important intercrystalline structural features are a systematic increase in crystal size with depth and a fairly constant 2:1 ratio between the length and width of the ice crystals. Similar features are well known from studies of the solidification of metals. The frequency distributions of plate widths, i.e., the distance between the centers of adjacent sub-grains measured parallel to the c-axis, commonly show significant positive skews. The average plate width increases with increasing depth in the ice sheet. Within the limited range of observations, a strong linear correlation exists between average plate width and the growth velocity of the ice. Plots of sub-plate widths vs sub-plate lengths show an extreme scatter and a slight increase in the model values of the plate length with increasing plate width. The packings of the sub-plates in sea ice are compared with packings observed in zinc and are found to be quite similar.

Hibler, W.D., III, **Model simulation of near shore ice drift, deformation and thickness**, *International Conference on Port and Ocean Engineering Under Arctic Conditions (4th)*, St. John's, 26-30 September 1977, Memorial University of Newfoundland, 1978, pp. 33-44, 15 refs.

Simulation results for sea drift, deformation, and ice thickness variations in the Arctic Basin are presented using a dynamic-thermodynamic model that treats the ice as a rigid plastic continuum. Using available observed atmostpheric and oceanic forcing data, numerical model simulations are made over a four-year long period employing one day time steps in a finite difference code with a resolution of 125 km. Drift, deformation, stress, and ice thickness time series from the simulation results in the near shore region off the Alaskan and Canadian North slope are reported and briefly examined in light of available observations.

Hoekstra, P., Osterkamp, T.E. and Weeks, W.F., **Migration of liquid inclusions in single ice crystals**, NTIS #AD-630 978, December 1965, 8 pp., 18 refs.

The migration of brine pockets of KCl and NaCl under the influence of a temperature gradient was investigated in single ice crystals. The observed migration velocities are compared with velocities calculated from a simple diffusion model using the data on electrolytic solutions available in the literature. Although the relative movements of KCl and NaCl pockets were consistent with the diffusion theory, the observed velocities were always less than the calculated. Neither the direction of the gravitational field nor the crystallographic orientation of the host crystal significantly influenced the rate of migration. It was also shown that the migration of solid KCl particles occurs at temperatures below the eutectic point. Two mechanisms are proposed that would impede the mechanical differentiation of salts that crystallize at high temperatures relative to salts that remain in the brine of sea ice. These mechanisms explain recent field observations that the SO sub 4/Cl ratio of sea ice does not increase with the age of the ice.

Iakovlev, G.N. (ed.), **Studies in ice physics and ice engineering**, Translation of Leningrad, Arkticheskii i Antarkticheski i Nauchno-issledovatel'skil institut.

*Trudy*, Vol. 3C0., Jerusalem, Israel, Program for Scientific Translations, 1973, 192 pp.

This collection of papers indicates some of the results obtained in studies of ice carried out during recent years. A wide range of subjects in many fields of ice research are dealt with: the structure of an ice cover, its elastic characteristics, methods for predicting the strength characteristics of an ice cover, techniques for breaking ice, theoretical and experimental laboratory work, etc. For individual papers see CRREL #27-2055.

Itaqaki, K. and Tobin, T.M., **Mass transfer along ice surfaces observed by a groove relaxation technique**, *International symposium on Isotopes and Impurities in Snow and Ice*, 28-30 August 1975, International Association of Hydrological Sciences, Publication No. 118, 1977, pp. 34-37, 6 refs., In English with French summary.

The mass transfer coefficients were measured using a groove decay technique on the (0001) planes of naturally and artificially grown H20 ice and artificially grown D20 ice at -10°C. In each case a viscous flow term contributed the most to groove decay in the longest wavelengths measured, while an evaporation-condensation term predominated in the shortest wavelengths measured. All other terms were found to be negligible. Large discrepancies between the decay constants obtained from measurements and the constants calculated from theory indicate that other mechanisms not considered in Mullins' theory may be responsible for the groove decay.

Kawasaki, S. and Umano, S., **Studies on sea water refrigeration concentration, Report 13: Studies on the nucleation and the growth of ice crystal in sea water**, U.S. Joint Publications Research Service, NTIS #AD-885 376L, 1971, 37 pp., 15 refs.

A study on the supercooling and freezing of sea water is described. The degree of supercooling of sea water samples is determined by the nature of the nuclei and that of the container walls. The interrelationships between such parameters as degree of supercooling, quantity of ice produced, and velocity of crystal growth are shown mathematically.

Kawasaki, S. and Umano, S., **Studies of sea water refrigeration concentration, I. Freezing temperature of sea brine**, U.S. Joint Publications Research Service, NTIS # AD-885 377L, 1971, 9 pp., 7 refs.

The results of f.p. determinations of samples collected in April and June 1953, and December 1956 on the coast at Qiso are reported. The f.p. of brine samples with a total salt content from 2.18-17.38 percent by weight was -1.13 to -13.27°C, that of samples with a salt content of 3.41-20.05 percent ranged from -2.21 to -17.84°C, and that of samples with a salt content from 12.83-24.80 percent (eutectic concentration) ranged from -8.225 to -22.927°C. The accuracy of the measurements was 0.02°C.

Keeler, C.M., **Snow and ice**, *American Geophysical Union, Transactions*, Vol. 52, No. 6, June 1971, pp. 295-301, 217 refs.

An increasing concern for the use of all available fresh water, the promise of increased engineering activity in the Arctic, and a growing demand for winter recreation facilities have all served as practical incentives for snow and ice research. This research is in the face of various prophecies that pollution of the atmosphere may result in the melting of global snow and ice, perhaps even within the lifetime of many investigators.

Khanina, S.K. and Shul'man, A.R., **Investigation of the flow of natural ice**, NTIS #ADA-026 677, May 1976, 15 pp., 8 refs.

The structure of natural ice from the Neva and Volkhov rivers and from Ladoga and Suzdal'lakes was investigated during Jan. - April 1948. River ice crystals resembled artificial ice crystals in size. Tests indicate that deformation is a function of time, the load, and the direction of application of the load in relation to the optical axis of the ice crystals. Maximum deformation occurred when the load was applied perpendicularly to the optic axis of the crystals. Deformation increased with time. The viscosity was less in monocrystals than in river ice.

Kingsbury, B.T. and Welsh, J.P., **Characterization of slush ice in the Great Lakes**, Coast Guard Research and Development Center, Groton, Connecticut, Final Report No. CGR/DC-34-75, November 1974.

The purpose of this study was to identify characteristics of slush ice and to develop techniques for their measurement. Slush ice is a mixture of fresh water ice and water. It becomes an impediment to navigation when wind and water current transport the ice fragments into a restricted channel or harbor. The characteristics of slush ice identified and measured were draft, ice to water ratio (surface aspect only), and ice particle size distribution. Draft was measured using a sonar transducer set on the bottom of a channel and echoing off the underside of the slush ice. The water to ice ratio was obtained from photographs of slush ice taken from a helicopter. The ice particle size distribution was obtained by physically measuring ice particles in the field.

Kobeko, P.P. and Marei, F.I., **Wetting and strength of adhesion**, July 1958, 6 pp., *Translation from Zhurnal tekhinicheskoi fiziki*, Vol. 16, pp. 277-282, 1946, 5 refs.

Unsuccessful attempts to develop a water repellant coating for deicing airplanes prompted an investigation of existing relationships between wetting and

strength of adhesion. An instrument, based on the leverage principle, was constructed to determine the force required for a hemispherically-shaped test item to break away from the ice to which it was frozen. Several wetting and nonwetting systems were tested. The average strength of adhesion for a polystryene-water system was 2.2 kg/sq. cm. The behavior of the polystyrene-water system was similar to that of other polymers, and to lacquers. Further experiments indicated that the large coefficient of expansion of the plastics and not their wetting-nonwetting properties caused this low adhesion strength.

Kovacs, A., **Density, temperature and the unconfined compressive strength of polar snow**, NTIS #AD-660 309, July 1967, 25 pp., 19 refs.

The relationships between several empirical and theoretical methods of determining the unconfined compressive strength of polar snow from depth-density and temperature profiles are discussed and graphically compared. Two unconfined compressive strength equations are proposed for snow at -10°C. The formulas take into consideration the decided changes in slope of the Young's and shear modulus curves at a density of 0.5 g/cu cm for Greenland snow. The slope changes signify that at this density a structural and, therefore, a strength change occur. Analysis of existing test data confirms this reasoning.

Kovacs, A., **Ice scoring marks floor of the arctic shelf**, *Oil and Gas Journal*, Vol. 70, No. 43, 23 October 1972, pp. 92, 97-98, 101, 103, 106, 26 refs.

Ice scoring on the Beaufort Sea shelf can be divided into three zones: 1) A coastal shelf zone where scoring may be very frequent but the resulting microrelief is shallow; 2) A mid-shelf zone with considerable contemporary scoring, which mixes the surface sediments to a depth of perhaps 5 ft, depending upon local sediments, destroying stratification, and oxygenating the sediments; and 3) An outer shelf zone where scoring to 30 ft has occurred but the frequency of scores decreases very quickly beyond the 150-ft depth. While considerable overlapping of scores exists between the 100 and 150-ft depth range, many of these scores are not of recent origin. This is predicated upon the observation that some of the scores are partially filled with sediment and upon recent estimates of ice keel depth distributions in the Beaufort Sea. Resulting calculations indicate that the possibility of encountering an ice keel 110 ft deep at a given location is less than once every 100 years. Probability of encountering keels less than 100 ft deep increases exponentially with decreasing depth.

Kovacs, A., Loken, O.H., and Mellor, M., **Sea ice morphology and ice as a geologic agent in the southern Beaufort Sea**, *Symposium on Beaufort Sea Coast and Shelf Research*, San Francisco, 7-9 January 1974, Arctic Institute of North America, 1974, pp. 113-164, 8 refs.

The paper gives a general account of ice conditions in the southern Beaufort Sea and makes a preliminary exploration of one of the important engineering problems created by ice over the continental shelf. Notes on the oceanic environment mention surface winds, currents, waves, temperature, salinity, bed relief, bottom sediments, and extent of ice cover. Three characteristic ice zones are defined (fast ice, seasonal pack ice, and polar pack ice), and for each one the genesis, morphology, activity, and distribution of constituent ice types are discussed, with special reference to ice ridges and the configuration of pressured ice. The occurrence, movement, and size distribution of ice islands are considered, and ice scoring of bed sediments is described. The bed-scoring problem is examined. The authors conclude that most keels have ample strength for gouging, that necessary sustained forces can be developed by wind shear over reasonable areas, and that first-year ice can transmit the needed thrust to ice islands or pressure ridges. The momentum of isolated ice masses was determined to be insufficient to cause significant gouging.

Kuroiwa, D., **Studies of ice etching: I. Application of thermal etching to the study of surface abrasion in ice crystals**, NTIS #AD-XL 624 199, May 1965, 26 pp., 8 refs.

Thermal etching ice and its application to the investigation of surface abrasion in ice crystals is explained. Investigations of surface abrasion in ice crystals provide fundamental information in the study of snow and ice friction. The technique of producing evaporation etch pits by the application of Formvar film to the ice crystal surface is described and the development of microcrystals by recrystallization is compared with the surrounding mother crystals. Experimental data are presented and discussed with emphasis on the development of thermal etch pits, scratches on different crystal faces, damage to the prismatic face, thermal etch channels on the basal plane, predominant orientation of etch channels on the basal plane, and etch-pit-free zones and stress concentrations around solid inclusions.

Landauer, J.K. and Pluah, H., **Measurements on anisotropy of thermal conductivity of ice**, NTIS #AD-094 686, April 1956, 5 refs.

A comparison technique is used to measure the anisotropy in the thermal conductivity of ice. Samples of laboratory grown monocrystals, glacial monocrystals, and polycrystalline commercial ice were studied. No effects due to the grain boundaries are observed. The experiments indicate that the conductivity in the direction of the c-axis may be about 5 percent greater than normal to it. The probable error in the results is about 2 percent. Analysis of the data leads to the conclusion that, if a difference in conductivity exists, it is less than 8 percent. More accurate experimentation

is necessary to specify the anisotropy with greater precision.

Langleben, M.P. and Pounder, E.R., **Acoustic attenuation in sea ice**, McGill University, Montreal, MacDonald Physics Lab., Report #S-14, June 1968, 21 pp.

A study is underway of the acoustic attenuation properties of sea ice. The transmitting transducer was driven by a sinusoidal signal whose frequency was swept mechanically over the frequency range 10 to 500 kHz. The suitably amplified signal from the receiving transducer was plotted against frequency on an X-Y recorder. No absolute power measurements were attempted, but the transmission path was reduced by stages and the resulting differences in received power compared. In a second series of laboratory experiments, small transducers were frozen at various positions through the ice sample to permit in situ power measurements. Results of laboratory and field measurement agree quite well on the pattern of attenuation with frequency, although the numerical values differ somewhat between different samples of ice.

Langleben, M.P., **Some physical properties of sea ice, II**, *Canadian Journal of Physics*, Vol. 37, No. 2, 1959, pp. 1438-1454.

Some properties of annual sea ice at mid-temperature latitudes are investigated. It is found that the salinity is comparable to, and the density much lower than, annual arctic sea ice. Permeability to air flow compares favorably to calculations based on the model of sea ice of Anderson and Weeks (1958). Small sample ring tests of ultimate tensile strength yield values ranging from 9.5 to 24.8 kg $cm^{-2}$ at test temperatures of -3.6°C to -17.2°C. Tensile strength appears to depend on crystal size rather than on brine content.

Lau, F. and Rossiter, J.R., **Physical properties of fast ice near Twillingate, Newfoundland, February-March, 1977**, Memorial University Center for Old Ocean Resources Engineering, Report #78-1, March 1977, 103 pp.

The physical properties of fast sea ice in Notre Dame Bay, Newfoundland, were measured in Feb. and Mar. 1977. Measurement of thickness, temperature density, salinity, and crystal structure were made at 10-cm depths through the ice at several sites, from a few weeks after ice formation to break-up. Typical properties measured at one site were: 45-60 cm for thickness, -2.0--4.5°C for temperature, 0.86-0.89 Mg/m3 for density, and 2.5 to 6.00/00 for salinity. The possible errors of the measured values were estimates as: F1 cm for thickness; F0.25°C for temperature; F1.2% for density; and F6% for salinity. The measurement procedures are described and suggestions for improvements are given. A quick, easily used heating technique was used to make thin sections for ice crystal study in the field. Although variations in crystal size, shape, and orientation can be observed, the size of air and brine pockets is greatly expanded using the heating technique.

Lavrov, V.V., **Temperature dependence of ice viscosity**, NTIS #AD-718 887, 1950, 7 pp., Translation from Zhurnal tekhnicheskoi fiziki, Vol. 17, No. 9, 1947, pp. 1027-1034, 6 refs.

The role and significance of crystalline structure in the study of the plastic properties of ice has been demonstrated. An anomalous change in the rate of plastic deformation of specimens of sufficiently regular crystalline structure occurs when they are subjected to sharp change in temperature, constituting a phenomenon of interest to the theory of plasticity. It has been demonstrated that the phenomenon of rest, well known in the literature on crystallography, holds for ice as well. A sufficiently well-grounded evaluation of the relation between the viscosity of ice, and temperature range of -3 and -23°C.

Lee, O.S. and Weeks, W.F., **Observations on the physical properties of sea-ice at Hopedale, Labrador**, *Arctic*, Vol. 11, No. 30, September 1958, pp. 135-155, 13 refs.

Results of field studies in 1955-1956 on the general physical properties of sea ice are reported, and the methods of measurement are described. The chacteristics of sea water during the freezing period are outlined, and the formation, structure, and salinity of the initial ice cover, the formation and characteristics of infiltrated snow-ice, the growth of the ice and influencing factors, and the density of the ice at various periods, and crack formation are discussed. Data are graphed on the salinity of sea ice formed during wave action and that of sheet-ice, the hourly averages of air and ice temperatures at various levels on a selected day, snow and slush density and thickness, observed slush levels and theoretical water levels, salinity of ice before and after the slush layer froze, and that of deteriorating ice. The orientation of sea ice c-axes and of infiltrated snow-ice c-axes are diagrammed.

Lee, O.S. and Weeks, W.F., **Salinity distribution in young sea ice**, NTIS #AD-284 938, February 1962, 13 pp., 21 refs.

Studies were conducted at North Star Bay (NW Greenland) during Oct-Nov 1956 to examine the lateral and vertical salinity variation in known types of natural sea ice. Sampling procedures and data analysis are described in detail. The data show that the standard deviation of the salinity values from closely spaced cored samples in sheet ice are always equal or greater than p/m 0.3 percent. In pancake ice, the standard deviation is usually p.m 1.0 percent. This uncertainty will produce a standard deviation of

approximately p/m 4 to 6 percent of the total brine volume in the sheet ice and p/m 11 to 19 percent in pancake ice. This accounts for a considerable portion of the scatter observed in studying the strength properties of sea ice.

Lee, T.M., **Method of determining dynamic properties of visco-elastic solids employing forced vibration**, NTIS #AD-434 085, November 1963, 10 pp., 7 refs.

The dynamic properties of visco-elastic solids are evaluated by using the forced longitudinal and torsional vibration techniques. A method of eliminating experimental difficulties due mainly to the coupling of sample with supporting system is introduced in using the maximum amplitude ratio of the free end of a sample to the end attached to a driver and the corresponding vibration frequency as a criterion. Experimental measurements of these values are sufficient to determine the dynamic properties of samples. The complex modulus is used to describe the stress-strain relationship for a visco-elastic solid. In the method presented, matching of natural frequencies of the sample and the driver is not necessary and the same driving unit may be used throughout the experiment. The expressions derived for longitudinal and torsional vibrations bear direct relationship between the measured items and the dynamic properties and are simple to use.

Lewis, E.L. and Weeks, W.F., **Sea ice: some polar contrasts**, *Symposium on Antarctic Ice and Water Masses*, Tokyo, September 1979, Scientific Committee on Antarctic Research, 1971, pp. 23-34, 44 refs.

It is difficult to think of any sea ice feature that occurs in the Antarctic that does not occur somewhere or at sometime in the Arctic. However, there are a number of interesting distinctions that can be made between the ice of the two polar regions. Many of these differences are caused by the land-locked nature of the Arctic Ocean as compared to the unrestricted Southern Ocean. In this paper we review these differences briefly and discuss both our current understanding of them and their importance.

Little, E.M.L. and Pounder, E.R., **Some physical properties of sea ice**, *Canadian Journal of Physics*, Vol. 37, No. 4, 1959, p. 443.

This preliminary study is based mostly on work done at a shore station in Shippegan, N.B., during the winter of 1956-57, with some data from an icebreaker expedition in the summer of 1956. The Shippegan site had unrafted ice, tides of 5 feet or less, and negligible fresh-water runoff. The thickness of the ice was about proportional to the square root of the freezing exposure. Tritium dating of sea ice is an unsatisfactory method because of variable tritium concentration in Arctic waters. The jaggedness of ice crystals is suggested as a measure combining effects of age and thermal regime. Measurements of specific gravity, salinity, electrical resistivity, and premeability profiles all show progressive changes in annual sea ice throughout the winter. The tensile strength of sea ice at -20°C was aroung 200 to 500 p.s.i., at various angles to the grain. For fresh-water ice, with stress parallel to the grain, it was in the range of 500 to 1000 p.s.i. Shear strengths, with the shear plane parallel to the grain, were 80 to 160 p.s.i. for sea ice at -20°C and 160 to 280 p.s.i. for pond ice, also at -20°C.

Lofgren, G. and Weeks. W.F., **Effective solute distribution coefficient during the freezing of NaCl solutions**, *International Conference on Low Temperature Science*, Sapporo, 14-19 August 1966, Proceedings, Vol. 1, Part 1, Sapporo, Institute of Low Temperature Science, Hokkaido University, 1967, pp. 579-597, 49 refs.

The variation in the effective solute distribution coefficient k [k equals salinity (ice)/salinity (solution)] is studied as a function of growth velocity (v equals 3x1/100 to 1/1000 cm/sec) and the solute concentration of the freezing NaCl solution (to 100 per mill). The data is from ice prepared by unidirectional freezing using controlled ice-surface temperatures of -20 and -70°C. The data is in good agreement with a relation suggested by Burton, Prim, and Slichter (BPS, 1953). When growth conditions are such that the solid-liquid interface becomes planar ("lake" ice forms), this relation still appears applicable. Substitution of the BPS relation in an ice growth equation allows the calculation of both the initial salinity and brine volume profiles for young salt ice assuming no brine drainage. The resulting profiles are in good agreement with observed young sea ice profiles and show appreciable salinity changes as a result of changes in the meteorological conditions during growth.

Mantis, H.T. (ed.), **Review of the properties of snow and ice**, NTIS #AD-696 397, July 1951, 156 pp., 167 refs.

Includes chapters on mechanical properties, strength of snow and ice, electrical properties, geometric properties, thermal properties, radiation properties, heat economy of the snow pack, phase relations, supercooling, and ice formation in open water. An extensive bibliography with abstracts appears pp. 108-156.

Martin, S. and Niedrauer, T.M., **An experimental study of brine drainage and convection in young sea ice**, *Journal of Geophysical Research*, Vol. 84, No. 3, March 1979, pp. 1176-1186.

In a series of experiments using a 1.6-mm-thick freezing tank, thin sections of salt water ice were grown that exhibit the same drainage features as natural sea ice. The tank design permitted photographs to be taken, while thermocouples mounted in the tank

walls recorded the temperature profiles within the ice. Convection was observed in both the skeletal layer and in the brine channels by the flow of dyed brine. Flow in the skeletal layer was cusplike in appearance, consisting of narrow downflow regions separated by broad upflow regions. Above the skeletal layer, several brine channels were also usually present in the ice, and convective overturning occurred in these channels. The convection caused temperature fluctuations of 0.05°C, which calculations show increase the vertical heat flux by 1%. The brine drainage channels, which were usually sloped 30° to 60° to the horizontal, always had isotherms tilted from 0° to 13° in the same direction. The brine channels move both horizontally and vertically through the ice by melting their lower walls and freezing on the upper walls. An analysis based on the heat flux due to brine channel convection shows that convection can drive these wall movements. Our observations suggest that most of the brine movement in the channels is caused by recirculation of water from below the ice. On a small scale we also observed the formation of brine pockets from brine tubes.

Matsumoto, A. and Nakaya, U., **Evidence of the existence of a liquidlike film on ice surfaces**, NTIS #AD-027 517, November 1953, 6 pp., 1 ref.

Experiments were made on the adhesive force between 2 ice spheres, 1.5-4.0 mm in diam., suspended on thin cotton filaments. The normal adhesive force, which tends to decrease with decreasing temperature, was measured by the inclination of a filament as the spheres separated. The ice spheres occasionally rotated before separation, and 2 or 3 successive rotations were noted with a 0.1 percent solution of NaCl. The phenomena may be explained by assuming the existence of a liquid film on the ice surface.

Maykut, G.A., **Energy exchange over young sea ice in the central Arctic**, *Journal of Geophysical Research*, Vol. 83, No. 7, July 1978, pp. 3646-3658.

A simple model of heat transport through young sea ice is combined with climatological data on air temperatures and incoming radiation in the central Arctic to predict how each component of the surface heat balance is affected by changes in ice thickness. Results indicate that during the cold months the net heat input to the atmosphere from ice in the 0 - 0.4-m range is between 1 and 2 orders of magnitude larger than that from perennial ice. Once the ice exceeds a meter in thickness, there is little change in any of the heat fluxes as the ice thickens. Although both the amount of absorbed shortwave radiation and the emitted longwave radiation depend on ice thickness, it is the turbulent fluxes that undergo the largest changes. The rate of heat exchange over thin ice is shown to be extremely sensitive to snow depth and the central Arctic, total heat input to the atmospheric boundary layer from regions of young ice is equal to or greater than that from regions of open water or thick ice.

Maykut, G.A., **On the heat and mass balance of the Arctic ice pack**, *Naval Research Reviews*, Vol. 31, No. 7, July 1978, pp. 17-35.

Noting the magnitude of error introduced by failing to include the effects of open water and young ice in estimates of heat exchange and total ice production conventionally derived from submarine sonar profiles, theoretical models for calculating thickness distribution for both thick and young ice are developed that simulate both the dynamic and thermodynamic processes. Using climatological heat balance data in conjunction with these ice models, it is possible to more accurately calculate growth rates that allow for seasonal changes in incoming solar radiation, snowfall, dependence of albedo in ice thicknesses, and variations in the oceanic heat flux. Interaction between ocean and atmosphere in the presence of a dynamic ice cover is apparently more vigorous than previously believed. Improvements in theoretical models should lead to greater utilization of currently extant high quality satellite and buoy data.

Nakaya, U., **Elastic properties of processed snow with reference to its internal structure**, NTIS #AD-277 541, October 1961, 25 pp., 8 refs.

Young's modulus was measured as a function of density and age hardening for snow processed by Peter and Snowblast millers during the summer of 1959 at Site 2 located 220 miles E. of Thule near 78 N lat. and altitude 7000 ft. For processed snow, as for naturally compacted snow, a linear ralationship exists for Young's modulus density at densities above 0.5 g/cu. cm and an exponential relationship for densities below this value. Thin section studies indicated that the number and size of bonds determine Young's modulus. Bonding begins a few hours after deposition by the snow miller; the bonds develop to approximately 0.2 mm in diam. some 20 days after deposition.

Nazarov, V.S., **Buoyancy of sea ice**, NTIS #AD-070 154, 1955, 2 pp., Translated from *Severny; Morskoi & Put'*, Vol. 11, pp. 62-63.

The inverse relationship between the buoyancy of sea ice and its density is applicable only to winter ice that has not been subjected to melting. The density of winter ice averages from 0.900 to 0.940 g/cu cm. Spring ice has an average density of 0.839 to 0.900 g/cu. cm due to melting and the formation of inner cavities. It is believed that these cavities eventually fill with water and that the corrected density of spring ice is about 0.977 to 0.993 g./cu. cm, which indicates reduced buoyancy. A table is presented for loads that can be moved over winter and spring ice of varied thicknesses.

Ono, N. and Tabata, T., **Ice study in the Gulf of Bothnia, III: observations on large grains of ice crystal**, Institute of Low Temperature Science, Hokkaido, Japan, No. 33, 1975, pp. 207-213.

In March, 1975, large grains of ice crystal were found in new ice formed on melt pools among shore-ice floes around the Norrbyskar Islands. Thicknesses of shore-ice around the islands ranged from 35 to 50 cm, its salinity was 0.7 percent and that of seawater, 4 percent. In the daytime, the shore-ice melted, new ice formed at night on melt water, less than 1 cm thick and 0.014 percent salinity. A large dendritic pattern appeared on each sample under sunlight, as large as 80 cm in diameter, showing that each is a large grain of ice crystal with the C-axis perpendicular to the ice surface. Interference figures are shown for three ice samples. It is considered that the low salinity of seawater and the melting and refreezing cycles of new ice are causes of formation of such large grains of ice crystal.

Ono, N., **Thermal properties of sea ice, IV: thermal constants of sea ice**, NTIS # ADB-000 929, January 1975, 19 pp., 14 refs., For Japanese original see CRREL #24-168.

A sea model is proposed for calculating the thermal constants of sea ice. The sea ice model consists of pure ice, brine at an equilibrium concentration, and spherical air bubbles dispersed uniformly both in the pure ice and in the brine. These bubbly ice and bubbly brine models are arranged in parallel with the heat flow passing through the model of sea ice. Thermal constants of sea ice, namely density, thermal conducitivity, specific heat, changes in heat contents, heat or fusion, and thermal diffusivity are theoretically defined and are calculated using this model as a function of temperature, salinity, and air bubble content of sea ice. The thermal diffusivity values derived from the observed temperature data were compared with theoretical values. Changes with the temperature in the derived value thermal diffusivity and the temperature dependency of the theoretical values were in fairly good agreement.

Parmerter, R.R., **A model of simple rafting in sea ice**, *Journal of Geophysical Research*, Vol. 80, No. 15, 1975.

A mechanical model is developed to describe the rafting of ice sheets of equal thickness. Rafting is one of the important deformation mechanisms in thin ice. The model predicts the force required to initiate rafting. This force is an upper bound for the force in pack ice. The model is also used to calculate the bending stress developed by rafting. The stress increases in proportion to the square root of ice thickness. Thus for a given ice strength there is a maximum thickness of ice that can raft without fracturing. For typical young ice properties, the calculated value of 17 cm is in good agreement with field observations.

Peschanskii, I.S., **Ice science and ice technology**, NTIS #AD-715 026, 1968, 66 pp., Translation from *Ledovedenie i ledotekhnika*, 2d ed., Leningrad, Gidrometeoizdat, 1967, p. 134-149, 160-171, 194-201, 328-335, 351-355, 367-379.

The properties of the ice cover are dependent both on the properties of the ice and on the characteristics of the ice cover itself. Among the characteristics determining the ice cover, other than the form of ice of which it consists, are its horizontal extent, thickness, temperature, strength, type of surface, and intactness. These characteristics of the ice cover are determined by its origin. Existing classifications of sea ice inadequately emphasize the role of the principal factors determining the origin of the ice cover and make difficult their quantitative evaluation. In contrast to the existing classification, the author has proposed a classification of the ice cover on the basis of its origin.

Ramseier, R.O., **Self-diffusion in ice monocrystals**, NTIS #AD-662 196, October 1967, 40 pp., 53 refs.

The self-diffusion of tritium, parallel and perpendicular to the optimal axis of naturally occurring and artificially grown ice monocrystals, was studied between -2.5 and -35.9°C. The artificial ice monocrystals were grown using a zone-melting technique. Activated samples were stored for several weeks, then sectioned by microtome and analyzed in a liquid scintillation counter to obtain the self-diffusion coefficients. The plane source solution of Fick's second law was used in treating the data. The diffusion coefficients were found to be identical for both types of ice. A slight anisotropy was found due to the geometry of the crystal. Based on the experimental data, it is concluded that the diffusion takes place by a vacancy mechanism and that entire water molecules are diffusing, i.e., molecular diffusion occurs.

Ramseier, R.O., **Some physical and mechanical properties of polar snow**, NTIS #AD-631 685, February 1966, 22 pp., 21 refs.

Specimens of snow from the South Pole were tested to investigate air permeability, ultimate compressive strength, and dynamic Young's modulus as a function of density. Anisotropy in a single layer of snow (snow between two summer crusts) was found in all three properties. Comparison with data for snow from Site II, Greenland, showed an empirical relation for both areas. Air permeabilities are different at the two sites because of time and meterological effects.

Riska, K. and Varsta, P., **State-of-art review of basic ice problems for a naval architect**, Technical Research Centre of Finland, Espoo, Ship Lab., Report No. BTT-SL-2 ISBN-951-38-0557-3, November 1977, 74 pp.

The structure of ice and the initial formation of ice cover are described. The occurrence and classification of ice in the Baltic are reviewed. The mechanical properties of ice, from the viewpoint of a naval architect, are examined from both theoretical and experimental standpoints. The problems of ice-going ships are studied and modeling techniques for ice-breaking and ice cover are discussed.

Ross, B., **Penetration studies of ice with application to arctic and sub-arctic warfare, Phase II Study**, Stanford Research Institute, Menlo Park, California, Naval Warfare Research Center, Report No. NWRC-3072, May 1967, 147 pp.

Impact tests with freely falling and explosively powered projectiles were performed on laboratory sea ice test slabs made from frozen seawater at Stanford Research Institute, and on Arctic sea ice in situ at Point Barrow, Alaska. In the experiments, particular attention was devoted to studying the mechanisms of penetration and perforation. Ranges of values investigated for the basic parameters were: impact velocity, 8-20 ft/sec and 50-494 ft/sec; projectile weights, 0.75, 9.69, and 41.5 lb; penetrator diameters, 5/8 in., 1-1/4 in., and 6 in.; penetrator profiles, blunt; temperature, +7 - +32°F; and sea ice salinity, 7.2 - 17.1 ppm. All tests were carried out at normal incidence except for one sequence on Arctic sea ice in which the angle of incidence was 17.3 degrees from vertical. Results of the tests indicate that a cylindrical, blunt-end penetrator was more effective in perforation than a corresponding penetrator with a conical end. The blunt penetrator, impacting at normal incidence perforated both laboratory sea ice and Arctic sea ice by expelling a cylindrical-conical shear plug from the test specimen. For this behavior, a mathematical model was constructed and a theoretical analysis developed from which the minimum impact velocity for perforation (critical velocity) was obtained. The critical velocity was found to be a function of projectile mass and diameter, and sea ice thickness, shear strength, tensile strength, and elastic modulus. The theory did not consider effects due to cratering.

Sander, G.W., Tien, C., and Yen, Y.C., **Experimental study of a melting problem with natural convection**, *International Heat Transfer Conference, 3rd*, Chicago, 7-12 August 1966, Proceedings, Vol. 4, New York, American Institute of Chemical Engineers, 1966, pp. 159-166, 13 refs., In English with German and Russian summaries.

An experimental technique has been successfully developed to study the effect of natural convection (thermal instability) on the melting rate of ice. Reproducible results were obtained by using homogeneous, bubble-free ice samples for the melting process. The problem of volume change due to phase transition or separation of the ice-water interface encountered when melting from below was solved by continuously adding water at the same temperature as the constant temperature bath that supplied heat for melting. Under certain temperature conditions irregularities in the interface, a result of convective motion, became very apparent and could be observed by visual means. By periodically measuring the amount of water added and varying the initial temperature of the ice sample and that of the heat source extensive results were obtained demonstrating the effects of these temperatures on the melting rates. The results from this experimental investigation are compared with those obtained from an analytical solution of the same problem.

Savel'ev, B.A., **Manual for the study of the properties of ice**, NTIS #AD-741 870, April 1972, 225 pp., numerous refs.

Chapters in the manual deal with: (1) The study of the structure of ice and snow by a recommended crystal optimal method. Procedure is given for preparing snow and ice sections, photographic reproduction, and comparative evaluation of the results. A method that summarizes many structural elements in a single diagram is presented. (2) Methods of investigating the chemical composition of ice, melt water, and brine. (3) Study of the liquid and solid phases of saline ice. (4) Methods of determining density and porosity. Special attention is paid to the method of radioactive logging used by A.V. Krasnushkin in 1959 in Antarctica. (5) Methods of analysis of gas inclusions in ice. (6) Basic methods of testing the strength of ice. (7) Study of thermal and radiation properties of ice.

Savel'ev, B.A., **Structure, composition, and properties of ice cover on marine and fresh water bodies**, U.S. Army Foreign Science and Technology Center, Technical translation in Report No. FSTC-HT-23-50-72, NTIS #AD-765 896, 547 pp., numerous refs.

An examination is made of the mechanical and physical properties of ice covers on marine and fresh water bodies. The author attempts to explain the principal phenomena determining the most important physical properties of ice.

Savrilo, V.P. (ed.) and Soqorodskii, V.V. (ed.), **Physical methods of studying snow and ice**, NTIS #ADA-030 818, August 1976, 242 pp., For Russian originals of this collection see CRREL #30-3598 through #30-3635.

Proceedings of a scientific symposium organized by the Order of Lenin Arctic and Antarctic Scientific Research Institute and the International Commission for Antarctic Research, Earth Sciences Section, Presidium of the USSR Academy of Sciences, which was held in Leningrad on 1-5 October 1973, are published in this anthology. These articles by Soviet and foreign

scientists reflect the results of research conducted in recent years in the following directions: 1. Electromagnetic methods for analyzing snow and ice; active and passive radar analysis of ice and snow cover. 2. Optical methods for analyzing snow, ice, and water. 3. Dynamic and static methods for analyzing the mechanical properties of ice and snow.

Stevens, H.W., **Viscoelastic properties of frozen soil under vibratory loads**, Permafrost: North American contribution to the Second International Conference, Washington, D.C., National Academy of Sciences, 1973, pp. 400-409, 11 refs.

This article pertains to frozen ground mechanics, ground ice, saturation, viscoelastic materials, vibration, mathematical models, thermal factors, and foundations.

Tsytovich, N.A., **Instructions for determining the cohesive strength of frozen soil**, NTIS #AD-715 072, 1970, 17 pp., 8 refs., Translation of Instruktivnye ukazaniia po opredeleniiu sil stsepleniia merzlykh gruntov. Materialy po laboratornym issledovaniiam merzlykk gruntov, No. 2, 1945, pp. 162-175.

Determination of the cohesive forces in frozen ground is discussed with emphasis on the method and theory of pressing steel spheres into the ground. This method was evaluated at the Institute of Permafrostology and shown to be accurate and readily applicable for laboratory and field investigations. An apparatus for pressing the spheres into the frozen ground to a 10-mm depth and measuring the penetration within 0.01 mm is described in detail, and observational procedures are outlined. The cohesive strength under loading varies considerably with time and thus the value must be determined both for the initial loading and after reaching a stable value. Equations characterizing these variations with time are suggested.

University of Minnesota, Institute of Technology, Engineering Experiment Station, **Interim report to snow, ice, and permafrost research establishment**, NTIS #AD-661 307, January 1950, 60 pp.

This report was written to analyze the requirements for and recommend an orderly program for research in snow, ice, and permafrost, including the use of existing facilities to accomplish the research. Military end points and corresponding problems are enumerated and the problems in turn reduced to fundamental operations, environmental factors, and properties. Twenty-seven research projects are listed with priority, and briefly described as to nature and scope. Among the appended information is a summary to the present status of knowledge of snow, ice, and frozen ground. The report is particularly complete in an appraisal of snow and ice. Frozen ground is treated much less thoroughly.

Weeks, W.F., **Arctic coastal and ocean engineering**, *Northern Engineer*, Vol. 2, No. 1, Spring 1970, p. 2.

This article pertains to sea ice, ice mechanics, and marine engineering.

Weeks, W.F., **Sea and lake ice**, *American Geophysical Union, Transactions*, Vol. 44, No. 2, June 1963, pp. 588-592, 43 refs.

A large number of papers on the properties and behavior of sea ice appeared during 1960-1962, dealing with ice formation and the prediction of freeze-up, thickness, and decay. Studies on salinity distribution indicate that the rate of migration of an individual brine pocket is limited by the diffusion of the solute in the brine pocket. Several studies of the ring-tensile strength of sea ice have been completed, and its geophysical aspects have been considered. The mechanics of deformation of ice sheets and the technological problems associated with the utilization of snow and ice for operational needs have been studied.

Weeks, W.F., **Sea ice properties and geometry**, *AIDJEX Bulletin*, No. 34, 1976, pp. 137-171.

This section discusses what is known of the six physical properties of sea ice (strength, modulus, Poisson's ratio, density, friction, and adhesion) that are believed to be most important in problems related to year-round offshore operations in the high Arctic. The status of our understanding of three of these--strength, modulus, Poisson's ratio--has been reviewed in some detail in the past (Weeks and Assur, 1967 and 1969). Here we stress more recent developments.

Weeks, W.F., **Structure of sea ice: a progress report**, National Research Council, Publication No. 598, 1958, Arctic Sea Ice Conference, Easton, Maryland, February 1958, pp. 96-98, 6 refs.

The initial crystals forming in sea water vary from squarish discoids to hexagonal dendrites. From 10-90 percent of the upper surface of the initial ice sheet formed in calm water consists of crystals with vertical c-axes, while in rougher waters the crystals tend to be pushed into a vertical position with the c-axes horizontal. The grain size increases linearly with depth. Inclusions are distributed in certain selected planes (0001) within individual crystals, so that sea ice consists of alternating layers of pure ice and brine. Ice platelets forming single crystals are completely separated by brine layers in the lower 2.8 cm., and ice bridges begin to interconnect these plates only above this level. The thermal conductivity in this skeleton layer is 25-50 percent greater perpendicular than parallel to the c-axis as a result of the insulating effect of the brine layers.

Weeks, W.F., **Understanding the variations of the physical properties of sea ice**, NTIS #AD-657 213, May 1967, 15 pp., 39 refs.

Information and test results are presented concerning the mechanism of growth, brine content, strength, structure, and dielectric properties of sea ice. Suggestions are given for improving methods of calculating growth conditions and a schematic drawing is given of the solid-liquid interface for sea ice together with photomicrographs of sea ice at low temperatures.

Weeks. W.F., **United States sea ice physics project 1954-1959**, *Polar Record*, Vol. 9, No. 63, 1959, pp. 553-555, 12 refs.

Studies conducted at Hopedale (Labrador) and Thule (Greenland) by the Air Force Cambridge Research Center, USA SIPRE, and the Navy Hydrographic Office on factors related to the traffic ability of sea ice are described. A theory on the variation in the strength of warm sea ice as a function of temperature and salinity was developed; seismic methods of determining ice thickness and elastic characteristics were established; and data on vehicular movement on sea ice under marginal conditions was accumulated. Preliminary measurements were also made on the physical properties of artificially flooded ice.

Wilson, C., **Climatology of the cold regions, Introduction, Northern Hemisphere, Part I**, NTIS #AD-656 447, June 1967, 141 pp., 323 refs., For Part II see CRELL #24-3402.

A review summary of the climatological environment of the Northern Hemisphere contains a general introduction to the cold regions and a discussion of geographic controls and meteorological aspects including: 1) the hemisphere surface in terms of configuration and relief, vegetation zones and permanent and seasonal ice and snow; 2) the general circulation and weather system dealing with the circumpolar vortex, sea-level pressure and cyclonic frequency, circulation system persistence, and surface weather associated with high latitude pressures; 3) the net radiation and heat balance.

Wilson, C., **Climatology of the cold regions, Southern Hemisphere**, NTIS #AD-674 185, May 1968, 77 pp., 281 refs.

This monograph summarizes the climatology of the cold regions of the Southern Hemisphere, which consist almost entirely of the Antarctic Continent. Comparisons with the northern cold regions are followed by a systematic treatment of general circulation, the energy budget, and meteorological elements forming the climate of the region. Thirty-two illustrations (many of several parts) and ten tables give climatological data, and a selected bibliography of 281 items provides complete coverage for further details.

Wilson, J.T. and Zumberge, J.H., **Quantitative studies on thermal expansion and contraction of lake ice**, *Journal of Geology*, Vol. 61, July 1953, pp. 374-383, 14 refs.

Field observations during the winter of 1951-1952 on Wamplers Lake in southeastern Michigan included measurements on the movement of the sheet of lake ice in response to air-temperature fluctuations. The following generalities resulted from the study. A temperature rise of 1°F/hr prolonged over a period of 12 hr on an 8-in. sheet is sufficient to cause thrust on a shore composed of unconsolidated glacial outwash containing some boulders. The direction of ice thrust against the shore is not everywhere orthogonal to the trend of the shore line on an elongated lake but may be oblique at certain points. Tensional fracturing of the ice due to rapid cooling results in one set of cracks that radiate from the central part of the lake and another set roughly concentric with the shore line.

Yakovlev, G.N., **Studies in ice physics and ice engineering**, National Science Foundation, Washington, D.C., Special Foreign Currency Science Information Program, 1973, 198 pp., Translation of Arkticheskii i Antarkticheskii Nauchno-Issledovatelskii Institut, *Trudy*, (USSR) Vol. 300, 1971, 219 pp., by R. Hardin.

*Static pressure of sea ice*; Method for predicting strength characteristics of ice cover; Experimental studies in an ice-research laboratory; scale effect as indication of ice-breaking mechanism; Division of the Arctic Marine ice cover into regions according to ice structure; Determination of elastic characteristics of an undisturbed ice cover using static and dynamic methods; Ice pressure on individual marine structures; Some unsteady-state problems in ice-cover dynamics; Melting of ice in hummocks; Isostatic phenomena on pack-ice floes; Studies of Antarctic fast ice; Radiation breakup of Antarctic fast ice; Sizes and shapes of congealed ice crystals; A trail calculation of icebreaker passability through sea ice.

**Development of ice mechanics test kit, final report**, Investigation made for U.S. Navy, Hydrographic Office, NTIS #AD-712 490, March 1950.

A portable test kit has been developed in which is included hand-operated equipment for penetrating ice to a depth of 15 feet or more and for obtaining ice specimens, together with equipment for measuring ice thickness, density, salinity, temperature, and compressive strength. With construction of necessary adapters, additional tests may be performed, such as tension, shear, and flexure strength tests. A specially-designed auger included in the kit is of particular interest providing hitherto unavailable equipment for drilling and coring ice.

# 2. Ice Dynamics, Prediction, and Growth

## A. General

Assur, A. and Weeks, W.F., **Fracture of lake and sea ice**, NTIS #AD-697 750, September 1969, 77 pp., 175 refs.

The increased activity in cold regions has made a thorough understanding of fracture in lake and sea ice quite desirable, inasmuch as this information has application to a number of problems of geophysical as well as engineering importance. This survey starts with a discussion of the structure of ice and the macro- and microstructures of sea and lake ice, as well as their chemistry and phase relations. Recent work on the direct observation of dislocations as well as the formation of cracks in ice is summarized. Formal ice-brine-air models for analyzing variation in ice strength are also reviewed. The results of the different types of tests are discussed and compared (compressive, indentation, direct and simple beams, shear, and impact). Scale effects are considered as well as the rapid strength deterioration experienced by ice sheets in the spring. Finally, a number of recommendations are made concerning future research in this field.

Bilello, M.A., **Method for predicting river and lake ice formation**, *Journal of Applied Meteorology*, Vol. 3, No. 1, February 1964, pp. 18-44, 5 refs.

Two sets of curves are developed that can be used to forecast the dates of: 1) first appearance of ice in the fall, and 2) ice formation from shore to shore on the Mackenzie River at Fort Good Hope, Canada. Similar curves, based on the same method, can be derived for sheltered harbor, lake, and river locations. The numerical constants necessary to develop these curves were obtained from a relationship between mean daily air temperatures and previously observed dates of ice formation. To apply the curves, an adjusted temperature record, based on a numerical constant (N) and daily air temperatures, is maintained starting in early summer. Subsequently, this daily-adjusted temperature is applied to the family of curves to provide a day-to-day forecast of the date of ice formation.

Bydin, F.I., **Growth of ice**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, January 1972, 12 pp., Draft translation of Gosudarstvennyi Gidrologicheskii Institut, *Issledovaniya Rek* (USSR), Vol. 5, 1933, pp. 105-109.

The following topics are discussed: secondary ice, the growth of ice, and destruction of the ice cover before the break-up.

Deryugin, A.G., **Snow ice and its significance in computing the thickness of the ice cover**, Arctic Institute of North America, Washington, D.C., January 1972, 32 pp., Draft translation of Gosudarstvennyi Gidrologicheskii Institut, *Trudy* (USSR), Vol. 148, pp. 29-44.

The process of snow ice formation is considered in this article, and a correction of the formula for computing the thickness of the ice cover, taking into account this phenomenon, is proposed.

Gerdel, R.W., **Characteristics of the cold regions**, NTIS #AD-695 661, August 1969, 51 pp., 64 refs.

The paper gives a brief introduction to total cold environments relating the characteristics of the cold regions to the problems produced that hinder man's activities in these regions. Discussed are the zonal temperature regimes, the various forms and aspects of snow and ice, frozen ground, the permafrost, and the atmospheric phenomena of the greenhouse effect, refraction, reflection, and luminance.

Kheisin, D.E., **Dynamics of the ice cover**, U.S. Army Foreign Science and Technology Center, Washington, D.C., Report No. FSTC-HT-23-485-69, 18 September 1969, 263 pp., Translation of mono **Dinamika ledyanogo pokrova**, Leningrad, 1967.

Large parts of the seas, lakes, and rivers of our country are covered with ice for long periods of time, and the Arctic Ocean, almost year round. Ice, floating on the surface of the seas, greatly changes the character of the surface wave action. Many technical problems are related to construction and the operation of hydro-technical facilities, and important problems of shipbuilding and navigation under icy conditions cannot be solved without consideration of the dynamic strength characteristics of the ice cover. The mathematical theory of wave processes developing in the ice cover floating on water under the effect of gravity and internal forces is outlined in this book. Such a statement of the problem encompasses both the purely oceanological aspect of the problem and strength problems, where the effect of a system of dynamic loads on the ice is examined.

Lee, Y. and Reismann, H., **Dynamics of a floating ice sheet**, *Journal of Hydronautics*, Vol. 2, No. 2, April 1968, pp. 108-111.

Civilian and military operations are frequently conducted on the surface of floating ice sheets. For reasons of safety and operational reliability it is often required to predict the deformation and stresses in such floating ice plates due to surface loading. The present dynamic analysis considers the deformation of a floating ice sheet of infinite extent subjected to

rapidly applied surface loads. Solutions are obtained within the framework of both improved and classical theories.

Michel, B., **Winter regime of rivers and lakes**, NTIS #AD-724 121, April 1971, 131 pp., 164 refs.

The monograph summarizes existing knowledge of river and lake ice surveys, heat balance on open water in winter, frazil, ice cover formation, ice breakup, and ice control.

Nikiforov, E.G., **Variations of ice concentration in conjunction with its dynamics**, Naval Oceanographic Office, Washington, D.C., Report No. N00-Trans-51, 1959, 29 pp., Translation of *Problemy Arktiki* (USSR), No. 2, 1957, pp. 59-71, by M. Slessers.

Variations in ice concentration and their factors are analyzed and formulated so as to disclose the correlation of the factors and the effects they produce which, in natural circumstances, are in constant change and interaction. In line with this, the methods used in computing variations in ice concentration are re-examined and the necessary improvements introduced.

Parmenter, Frances C., **Spring ice migration near Newfoundland**, *Monthly Weather Review*, Washington, D.C., Vol. 100, No. 9, September 1972, pp. 690-691, National Environmental Satellite Service, NOAA, Suitland, MD.

During spring 1972, satellites observed the formation, changes, and breaking-up of the pack ice along the Labrador Coast. According to the U.S. Naval Oceanographic Office (1972) and Kniskern (1972), the pack ice extended farther south and east this year than in any season during the last 20 yrs. This year's increase in ice pack was attributed to the lower-than-normal (4-6°F below normal) temperatures during the winter and spring. A record accumulation of ice, 32-in. thick, was reported at St. Anthony, Newfoundland, in March. A series of APT photographs (ESSA-8) shows the changes in ice along the north and east side of Newfoundland.

Santeford, H. and Smith, J., **Advanced concepts and techniques in the study of snow and ice resources**, National Academy of Sciences, National Committee for the International Hydrological Decade, Washington, D.C., Pacific Southwest Forest and Range Experiment Station, Berkeley, California, Cold Regions Research and Engineering Lab, Hanover, New Hampshire, Report No. ISBN-0-309-02235-5, July 1974, 785 pp.

The volume's purpose is threefold: To foster expanded and continuing cooperation among the various people working in the snow and ice field; to alert these people to the potential impact of new technological advances on the study and management of snow and ice resources; and to acquaint people working in related fields with the problems and complexities of the snow and ice medium. Major topic headings are: information needs and distinguishing characteristics, information systems, radar techniques, remote sensing techniques, nuclear techniques, and miscellaneous techniques.

Schule, J.J., Jr. and Wittman, W.I., **Comments on the mass budget of arctic pack ice**, Naval Oceanographic Office, Washington, D.C., Report No. NOO-IR-67-17, 30 March 1967, 38 pp.

It is argued that deformation of the ice canopy has been neglected in past computations and considerations of the mass budget of pack ice in the Arctic Ocean. Evidence is presented to indicate that in the Canadian Basin alone, 13 to 18 percent of the ice area is covered by pressure ice considerably thicker than the 6 to 14 feet usually considered the average thickness of polar ice. A geometrical model based on empirical observations of under-ice, surface, and subsurface features is offered to permit computations of the volume of sea ice contributed by pressure ice. This model suggests that 1:3.3 is a realistic ratio between the above-water and underwater portions of an ice pressure ridge. Seasonal and spatial data from two years of aerial surveys on the frequency and height of ridges are presented, showing maximal values in winter near the North American coastlines. Similar data are presented on ice concentrations, stage of ice development, and the distribution of open and refrozen water throughout the Arctic Basin. Extensive submarine echo sounding data on the frequency of ice of various thicknesses corroborate the existence of larger amounts of open water - 15 percent more in summer - than previously estimated over large portions of the Arctic Basin.

Takizawa, T., **On the coefficient of kinematic eddy viscosity of pack ice**, Low Temperature Science, Ser. A, Physical Sciences, Sapporo, Japan, No. 34, 1976, pp. 181-186, refs., In Japanese with an English summary.

On the assumption that an ice field is a highly viscous fluid, the internal stress R may, in analogy with the Navier-Stokes equation, be expressed by R = .RHO .. SUB i.hk.SUB i..DELTA ..SUPER 2.U.SUB i., in which .RHO ..SUB i., is the ice density, h is the ice thickness, K.SUB i is the horizontal kinematic eddy viscosity coefficient of ice, U.SUB i is the ice velocity, and .DELTA ..SUPER 2 is the two-dimensional Laplacian operator. The velocity of ice off the coast of the Sea of Okhotsk was determined by radar images. The drift velocity of ice is expressed by U.SUB i. = A ln z + B, A = U.SUB i..@.k, and B = -A ln z.SUB o., In which Z, U.SUB i..@., k, and z.SUB 0., respectively, are the distance from the coast, the friction velocity, the von Karman constant, and the roughness parameter. The coefficient of eddy viscosity K.SUB i. = kU.SUB i..@.z is computed at the boundary layer as K.SUB i. = 0.4z. In the solution of the equation of motion outside the

boundary layer, it is assumed that K.SUB i. is the same as at the edge of the boundary layer. The thickness of the boundary layer is given approximately by .DELTA . .APPROX. . U.SUB i..@., L/V.SUB i, in which V.SUB i, is the velocity outside the boundary layer and L is the distance from the leading edge, where the boundary layer begins. A value of K.SUB i. of the order of 10.SUPER 6.cm. SUPER 2./sec is obtained.

Treshnikov, A.F., **Problems of the Arctic and Antarctic**, Office of Polar Programs, National Science Foundation, Special Foreign Currency Science Information Program, Washington, D.C., Report No. TT-75-52082, 1978, 214 pp. Translation of *Problemy Arktiki i Antarktiki* (USSR), Sbornik Statei, No. 43, 1974, by Y.V. Kathavate.

This volume includes important papers read by Soviet scientists at the symposium on Thermodynamic Interactions between the Atmosphere and the Ocean in the Arctic. This symposium was held in Leningrad during September 25-30, 1972. The major topics discussed relate to interactions in the atmosphere-ocean system in the Arctic. The interactions are broadly divided into: dynamic interactions with the participation of polar ice, and thermal interactions as influenced by the ice over the strongly disturbed underlying surface. The contributors have described the physical mechanism of thermodynamic interactions and proposed mathematical modelling of these processes and their experimental studies.

## B. Lake Ice

Ayers, J.C. and O'Hara, N.W., **Stages of shore ice development**, *Conference on Great Lakes Research (15th)*, University of Wisconsin, Madison, 5-7 April 1972, Proceedings, Ann Arbor, Michigan, International Association for Great Lakes Research, 1972, pp. 521-535.

Field observations and photographic operations were conducted throughout the winters of 1969-1970 and 1970-1971 to determine the sequence of events and processes involved in the development of the shore ice complex in fresh water. The study was conducted along the eastern Lake Michigan shoreline, with the major effort concentrated on the beaches adjacent to the Donald C. Cook nuclear power plant south of Benton Harbor, MI. Based upon a systematic series of routinely recorded photographs and upon observations conducted during critical periods of ice formation and destruction, a sequential pattern of events, depicting the stages of shore ice structural development, was identified. Observations and photographs were recorded from aircraft and from a ship, and on the ground in the investigation area. The shore ice complex first produces an icefoot composed of two ridges of onshore ice, followed by the formation of a frozen lagoon of brash ice and an outer barrier developed during the coldest part of winter. Finally, a field of floe ice may form for a limited time, reaching offshore to a distance of at least 17 km. The developmental stages of ice ridge and lagoon formation and destruction are dynamic and changing. The exterior ice field, second outer ice barrier, and lagoon are transient and apt to be carried away as the result of wave flexing, wind, and current movements. Ice ridges and lagoons can be broken and breached by stream and wave action and reduced in height by sand-melting. However, as long as the weather and water remain sufficiently cold, the rejuvenating processes will restore ridge and lagoon continuity when exposed to the open lake.

Bates, R.E., **Winter thermal structure and ice conditions on Lake Champlain, Vermont**, NTIS #ADA-027 146, June 1976, 22 pp., 9 refs.

The thermal structure and ice conditions of Lake Champlain, a mid-latitude large lake, near Shelburne Point, Vermont, were studied during the winter of 1974-75. The lake was instrumented to a depth of 8.5m with a string of highly calibrated thermistors, connected to a data logger on shore, which recorded water temperatures every four hours. An ice mooring system was developed to anchor the thermistor string so that ice and water temperatures could be obtained at known levels. This temperature recording system measured vertical and horizontal variations in ice and water temperature regimes during ice formation, growth, and decay. Meteorological data were measured during the winter period November 1974 through March 1975 at the site. Ice stratigraphy was determined for the ice at the site at its maximum seasonal growth for comparison with ice from St. Albans Bay (at the northern end of Lake Champlain), which had formed earlier. Correlations were determined between ice growth and accumulated degree days of freezing. The operation of a bubbler system installed near the measurement site around a service dock was observed.

Browman, Ludvig G., **Determination of the micro-level temperatures during lake cooling, ice formation, ice melting, and the break-up of the ice cover of a mountain lake**, Montana State University, Bozeman, Water Resources Research Center, Report No. 40, 15 July 1973, 17 pp.

The primary objective was to determine the micro-level temperatures during lake cooling, ice formation, ice melt, and the break-up of the ice cover of a mountain lake. The observations were carried out on Holland Lake, Montana, which is located west of the Continental Divide at an elevation of 1,225 meters, is roughly 165 hectares in area with a maximum depth of 48 meters. It is a dimictic, oligotropic lake surrounded by a complex of a Douglas firlarch forest.

Fremling, S., **Dependence of lake ice-covers on weather, snow and water**, *Hydrologi och Oceanografi*, Meteorologiska och Hydrologiska Institut, Stockholm, Sweden, No. RHO 12, 1977, 113 pp., refs.

A thorough monographic treatment of the formation, nature, growth, and decay of lake ice under different conditions of weather, cloudiness, wind, snow cover, and water is presented. Eleven chapters cover 1) cooling of a lake in autumn, freeze-up, and different kinds of lake ice (clear and white); 2) the growth of clear ice (heat flux through open water, snow-free, and snow covered ice); 3) growth of snow-ice; 4) thickness of lake ice; 5) deflections, folds, and thrusts caused by temperature changes; 6) transport of sensible heat from water to ice in a calm lake; 7) effect of running water through and within the lake (large and small, deep or shallow); 8) effect of heat and radiation in the air on ice cover; and 9) ice breakup. Many graphs, curves, maps, and diagrams illustrate the theoretical and empirical examples or processes.

Marshall, E.W., Wilson, J.T., and Zumberge, J.H., **A study of ice on an inland lake**, NTIS #AD-043 143, April 1954, 78 pp., 19 refs.

The final report is given on laboratory and field studies on ice of both small and large lakes in the Great Lakes areas during 1950-1953. The 3 main topics discussed are: development of a genetic classification of lake ice; studies of the crystallinity of lake ice; studies of the crystallinity of lake ice from the descriptive and genetic viewpoints; and the thermal push of an ice cover. The two main types of ice cover occurring in the area are classified as sheet and agglomeritic

ice. Four ice textures were identified: granular, columnar, porphyritic, and tabular. Ice push on Wamplers Lake (SE Mich.) amounted to about 2 ft. each winter, averaging 2 in. each cycle.

Ragle, R.H., **Formation of lake ice in a temperate climate**, NTIS #AD-443 794, August 1963, 22 pp., 13 refs.

The formation of lake ice in a temperate continental climate was studied during the winter of 1956-1957 at Post Pond, Lyme, New Hampshire. In the thirty-six blocks of ice studied, four textures and three structures were observed. The textures, tabular, columnar, granular, and crenulate, are discussed in terms of relative growth velocity. The structures were Forel striations, Tyndall figures, and bubbles. Strain shadows, a structural feature, were also observed. The average crystal area increased with increasing ice thickness. Generally the rate of increase was greater toward the center of the lake. However, within a pronounced bubble layer, which was continuous through a horizontal plane in the lake-ice sheet, the average crystal area ceased to enlarge. The lake-ice sheet grew both from the top and bottom with individual crystals growing most rapidly in the direction of their a-axes. Downward growth was by crystals that had the plane of their a-axes aproximately vertically oriented. These crystals grew rapidly, eliminating those crystals whose a-axes were less favorably oriented. The upward ice growth was caused by water flowing on the original upper ice surface and freezing.

Wagner, W.P., **Ice movement and shoreline modification, Lake Champlain, Vermont**, *Geological Society of America, Bulletin*, Vol. 81, No. 1, January 1970, pp. 117-126, 34 refs.

Measurements and observations of ice movements and shoreline modifications were made in 1968 on Lake Champlain, with detailed study on Shelburne Bay, near Burlington, Vermont. These investigations showed that distinctive ice movements on Shelburne Bay were caused by lake level rises, ice and snow ablation, and ice temperature fluctuation during the period of complete ice cover, and by wind action during ice breakup. Measured ice expansion and contraction movements can be approximated by theoretically considering the ice cover as a uniformly heated plate. Shoreline modification, in particular ice rampart formation, is very limited on Lake Champlain due to the continuous snow cover, the development of numerous pressure ridges, the relatively short period of partial open water, and the weakened condition of the ice during ice breakup. Factors controlling ice-sediment lateractions on Shelburne Bay are particle size, steepness of bottom slope, and shoreline configuration. Fine particle size, gentle bottom slope, and shoreline embayments together are associated with unrestricted ice movements and only minor ice ramparts.

## C. Sea Ice

Aagaard, K. and Coachman, L.K., **Arctic oceanography**, *Oceans*, Menlo Park, California, Vol. 6, No. 2, March/April 1973, pp. 24-31.

This article presents a review of the scientific and practical importance of research in Arctic oceanography, of the methods used in such research and of some results of Arctic oceanographic studies. The scientific value of research in Arctic oceanography is considered in understanding the world's climate, in possible modification of climate, and in economic exploitation of the Arctic. The oceanographic investigation methods involving the method of drifting ships (the FRAM, the MAUD, and the SEDOV,) drifting ice stations or ice islands, aircraft surveys, observations from submarines, ice breakers, and automatic sensing and transmittal are described. The present knowledge is summarized on water masses, currents, wind-driven and convective circulation in the Greenland Sea and water masses, currents, and ice cover in the Arctic Ocean. The United States, Canadian, and Soviet organizations engaged in oceanographic research in the Arctic and the AIDJEX experiment are discussed.

Aagaard, K. and Haugen, D., **Current measurement in possible dispersal regions of the Beaufort Sea**, *Environmental Assessment of the Alaskan Continental Shelf*, reports for the year ending March 1977, Vol. 14, March 1977, pp. 39-95.

The objective of this work is to obtain long-term Eulerian time series of currents at selected locations on the shelf and slope of the Beaufort Sea. Such measurements are necessary to describe and understand the circulation on the shelf and the exchange between the shelf and the deep Arctic Ocean. At least in late winter, the currents on the inner shelf appear to be slow. Long-term mean currents are extremely small. The two measurements made north of Norwhal Island showed these small displacements to have been west-southwest. On the outer shelf an entirely different situation prevails. Measurements made at 100 m under the ice from May-September showed the flow to reach over 55 cm sec-1 and even over a 3-month period the mean flow was 13 cm sec-1 toward the east. The most remarkable feature observed was the dominance of the motion by low-frequency variations with a typical time scale of 10 days. These oscillations represent bursts of speed as high as 50 cm sec-1 or more; they are directed eastward and are aligned approximately with the shelf edge. The implication of these measurements with respect to the transport and dispersal of pollutants on the Beaufort shelf is that the ice-covered inner and outer shelf represent very different advective regimes. Over the former, currents are weak and net displacements are small. However, over the outer shelf there are strong currents and pollutants can be transported very long distances.

Aagaard, K., **Standard measurements in possible dispersal regions of the Beaufort Sea**, *Environmental Assessment of the Alaskan Continental Shelf*, reports for the year ending March 1977, Vol. 14, March 1977, pp. 473-507.

Through a series of CTD sections across the Beaufort Sea shelf the seasonal hydrographic sequence from fall to spring in one year, and from fall to winter the next, have been traced. Not only are there large seasonal changes in the hydrography, but conditions are also different from one year to the next. The Beaufort Sea shelf is certainly not neutral with respect to the Arctic Ocean to the north. Rather, there are one or more forms of interaction, in which water and the substances it transports are exchanged between the shelf and the offshore regions. The most dramatic evidence of exchange is the series of four sections from fall 1976, in which an intense subsurface current core appears to be sweeping up the slope and onto the shelf, flooding at least one section to the innermost station with dense, saline water. The general thrust of the work is toward understanding the diffusive and advective processes, which transport and disperse pollutants and substances of biological and geological importance.

Ackley, S.F., Hibler, W.D., III, Kovacs, A., and Weeks, W.F., **Differential sea ice drift**, NTIS #ADA-007 733, March 1975, 37 pp., 35 refs.

Measurements of mesoscale sea ice deformation over a region approximately 20 km in diameter were made over a five-week period in the spring of 1972 at the main AIDJEX camp in the Beaufort Sea. They have been analyzed to determine nonlinearities in the ice velocity field (due to the discrete small-scale nature of the ice pack), as well as a continuum mode of deformation represented by a least squares strain rate tensor and vorticity. The deformation rate time series between Julian day 88 and 113 exhibited net areal changes as large as 3% and deformation rates up to 0.16% per hour. A comparison of mesoscale strain measurements with the atmospheric pressure field and the wind velocity field indicated that the ice divergence rate and vorticity followed the local pressure and wind divergence with significant correlation. For low atmospheric pressures and converging winds, the divergence rate was negative with the vorticity being counterclockwise. The inverse behavior was observed for high pressures and diverging winds. This behavior agreed with predictions based upon the infinite boundary solution of a linearized drift theory in the absence of gradient current effects and using the constitutive law proposed by Glen for pack ice.

Ackley, S.F., Hibler, W.D., III, Kovacs, A., and Weeks, W.F., **Differential sea ice drift I: spatial and temporal variations in mesoscale strain in sea ice**, *AIDJEX Bulletin*, No. 21, July 1973, pp. 79-113, 14 refs.

Measurements of mesoscale strain in sea ice were carried out over a five-week period in spring 1972 at the main AIDJEX camp in the Beaufort Sea. They have been analyzed to determine inhomogeneities in the strain as well as a least squares strain tensor time series. The least squares divergence between Julian day 83 and 112 exhibited five significant strain events consisting of dilatation followed by convergence. Net areal changes were as large as 3%. Data taken every three hours indicated divergence rates up to 0.12% per hour and shear rates as large as 0.10% per hour. In the principal axis coordinate system, the events typically exhibited a much larger compression (or extension) along one axis than along the other. It was found that by using a number of strain lines 8 km or longer the average strain rate tensor could be calculated with rate magnitudes larger than the inhomogeneity variation (variability of the average strain due to inhomogeneities). The inhomogeneity variation was found to scale inversely with the square root of the average length of the strain lines and to be only slightly dependent on frequency for frequencies above one cycle per day. The vorticity is, in most cases, similar to the rotation of the central station of the array and may be adequately estimated by calculating the average rotation of a set of randomly oriented strain lines. Spectral and cross-spectral studies indicate that sampling intervals of up to 10 hours are generally adequate for resolving low-frequency strain rates without intolerable aliasing, that low-frequency events show significantly greater spatial correlation than do higher-frequency events, and that there is significant coherence in the divergence rates of the different-sized arrays at approximately two cycles per day (in individual spectra these peaks are largely masked by random ice motion every 12 hours). Longer time series of several months are needed to adequately resolve the low-frequency behavior of the ice.

Ackley, S.F., **Sea ice studies in the Weddell Sea region aboard USCGC BURTON ISLAND**, *Antarctic Journal of the United States*, Vol. 12, No. 4, October 1977, pp. 172-173, 2 refs.

Sea ice studies in the Weddell Sea aboard BURTON ISLAND consisted of ice salinity measurements on meltwater from ice cores and thickness measurements taken in drilled holes. Floes in the northern regions were generally thicker than 2 m and in two regions exceeded 3 m on average. At higher latitudes in the middle of the Weddell Sea ice thicknesses exceeded 3.5 m. The thinnest ice was measured at the southern-most locations. It is concluded that advection is an important component in accounting for ice distribution in the Weddell Sea. In vivo fluorescence measurements of core meltwater revealed apparent relationships between ice salinity and biological activity (ice algae).

Ackley, S.F., Hibler, W.D., III, and Weeks, W.F., **Sea ice: Scales, problems and requirements**, *Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources*, Monterey, California, National Academy of Sciences, Washington, D.C., NTIS #AD-787 130, 1974, pp. 255-267, 21 refs.

Sea ice can be examined on a variety of spatial scales that range over 10 orders of magnitude. The smallest scale, the microscale, is distinguished from other scales by the greatest importance of changes in the growth conditions on the structure of the resulting ice and the controlling effect of these structural variations on its small scale (<10 m) property variation. The greatest need is for compact instrumentation that is capable of rapidly specifying by non-destructive methods the internal state of the sea ice. When observations on the mesoscale (100 m-50 km) are considered, the micro-structural properties of the ice rapidly become of less importance as the scale length increases, being replaced by effects produced by ensembles of ice features such as floes, leads, and pressure ridges. Instrumentation to accomplish most aspects of mesoscale experimentation is both expensive and relatively untested under Arctic conditions. The mesoscale is also the natural scale for the utilization of remote sensing systems operation from aircraft. However, for the results of such remote sensing flights to be useful, techniques are needed for rapidly analyzing and distributing the data. The most important equipment development problem as related to mesoscale studies is the present lack of an instrument that remotely measures ice thickness. On the macroscale (>100 km) most information would have to be provided by satellite-based remote sensing systems coupled with arrays of data buoys sited in the ice. The problems with the satellite-based remote sensing data are, as in the mesoscale, primarily related to difficulties in rapid analysis of the images in a format that can be used in current numerical efforts.

Andrews, J.T., Barry, R.G., and Mahaffy, M.A., **Continental ice sheets: conditions for growth**, University of Colorado, Boulder, *Science*, Washington, D.C., Vo. 180, No. 4218, 5 December 1975, pp. 979-980.

The conditions required for the development of major ice sheets in eastern Canada appear to have been approximated by those of the Little Ice Age in the 17th through the 19th centuries. Former extensive snowbanks from this period have been mapped from lichen-free terrain visible on Earth Resources Technology Satellite imagery. The climatic changes required to initiate the necessary snow line lowering may involve only a major summer cooling. Simulations with an ice-flow model reproduce plausible ice centers, but the rate of ice sheet buildup is slower than that suggested by geological evidence of world sea level lowering from 120,000 to 115,000 years B.C.

Arctowski, H., **Ice, sea ice and pack ice**, NTIS #AD-881 363, 1971, 55 pp., 35 refs.

A summarized and coordinated account is given of personal observations made during the expeditions of the BELQICA. Ice conditions at the edge of the pack, the freezing of sea water, ice growth, transformations of young sea ice, the characteristics of old ice and snow on the ice, the formation of blue ice and move on ice floes, the effect of wind on the ice, the characteristics of ice fields, icebergs, and the formation of areas of open water, crevasses, and pressure ice are discussed, and representative data are tabulated.

Arya, S.P.S., **Drag partition theory for determining the large-scale roughness parameter and wind stress on the Arctic pack ice**, *Journal of Geophysical Research*, Vol. 80, No. 24, 20 August 1975, pp. 3447-3454.

A simple drag partition theory is developed for the classical problem of boundary layer flows over regular arrays of two- or three-dimensional roughness elements. The theoretical expression for the ratio of the form drag on these elements to the total drag is shown to be in good agreement with wind tunnel observations. It is used for determining the contribution of form drag on pressure ridges to the total wind stress on the Arctic pack ice. The theory also lends to an expression for the large-scale roughness parameter as a function of mean ridge height, ridging intensity, small-scale or local roughness parameter, and an average from drag coefficient.

Assur, A., **Breakup of pack-ice-floes**, Kingery, W.D. (ed.), Cambridge, Massachusetts: MIT Press, 1963, pp. 335-347.

Long-wave cracks are mathematically analyzed on the basis of plate mechanics, and other forms of cracks are discussed. Long-wave cracks form with complete disregard of thickness and shape of the floes. They form instantaneously; the crack propagation is fast; there is no way to predict the location of a crack to be formed; and the ice flow, once split, drifts apart in a matter of minutes. Parallel-edge cracks running closely alongside existing edges are by far the most common. They form 12 to 15 m from the edge under combined bending and buckling originating from the pressure exerted from a neighboring floe. Perpendicular-edge cracks, which form at fairly uniform distances of 50 to 100 m apart, are more dangerous for the existence of an intact ice floe. The potential danger of perpendicular cracks lies in the forces created under the shearing action of adjacent ice floes. The moment originated by these forces may be enough to propagate a perpendicular crack (scissor crack) across an ice floe and separate a portion of it. Subsequent shear motion between the pieces of the ice floe may produce shearing cracks on the base of projecting corners.

Assur, A., **Growth of ice in thickness (Uber das Dickenwachstum des Eises)**, *Deutsche Hydrographische Zeitschrift*, Vol. 4, 1951, pp. 72-74, 6 refs., In German with English and French summaries.

It is shown that an incorrectly determined coefficient of the thermal conductivity of ice was used in various computations. A value of 0.0055 cal./cm./sec./C is suggested for use in practical calculations. The introduction of a reduction factor in equations used to determine ice thickness growth is suggested. The reduction factors calculated from various measurements varied between 0.3 and 0.8. The differences are chiefly ascribed to varying snow conditions on top of the ice.

Austin, T.S., **Changes and challenges in ocean data and information services**, *Sea Technology*, Vol. 19, No. 2, February 1978, pp. 12-14.

The Alaskan Outer Continental Shelf Environment Assessment Program (OCSEAP), a project of the NOAA, is used by the USDI to evaluate the ecological problems of oil and gas exploration, development, and production on the Alaska OCS. OCSEAP also collects data from other areas of the U.S. Problems dealt with include the energy crisis, ocean and air pollution, climatic deviations, world food shortages, and effective utilization of the coastal zone. The EDS (now known as the EDIS) provides data on ecological conditions to assess potential problems for such areas as Alaskan pipeline construction and the OTEC proposals for a 1- and 5-MW test facility to be built by 1981. The EDS helps assess problems of oil spill damage using models based on meteorological and oceanographic data. A strategic Petroleum Reserve stored in leached-out caverns in salt domes in the Gulf Coast area was proposed; EDS will assess problems of disposal of the salt in the ocean. EDS and GARP collaborate to assess climate anomalies using data from atmospheric and ocean studies, energy changes, snow and ice masses, and land surfaces. EDS/NOAA and NASA were collaborating to determine food shortage problems due to climate anomalies. The data will be used by the Dept. of Agriculture and foreign governments in a Large Area Crop Inventory Experiment. Other EDS projects include studies to help establish Regional Coastal Information Centers to better develop marine and coastal resources.

Baranov, G.I., Ivchenko, V.O., Kheisin, D.E., Maslovskii, M.I., and Treshnikov, A.F., **Wind drift of Antarctic sea ice**, NTIS #ADA-041 250, July 1977, 22 pp., 13 refs., For Russian original see CRREL #31-256.

Using a hydrodynamic ice drift model, which allows for interaction of icebergs among themselves, general schemes for average monthly ice circulation around Antarctica are given. A companion chart of solid and breakup zones is also included. The possibility of drawing up a map of solid ice zones based on the records of the forced drift of the Ob in 1973 is discussed.

Barber, F.G., **Beaufort Sea box model of ice**, Canadian Marine Sciences Directorate, Ottawa, Manuscript Report Series No. 43, 1977, pp. 255-258, refs.

A box model for analyzing ice transport, particularly in the Beaufort Sea, is presented. It consists of a matrix of continuity equations in which the observed change in the volume of ice in a time interval .DELTA .t is a function of the volume of ice produced, the volume of ice melted in a region i, and the transport of ice across the boundary from region i to region j in a time interval .DELTA .t; .DELTA .t is the observed period and also the period of transport from region i to region j. The use of the model is described; its application is illustrated; and its relevance to problems of oil spills and to concepts of processes and distributions in the Beaufort Sea is discussed.

Bilello, M.A., **Formation, growth, and decay of sea ice in the Canadian Arctic archipelago**, NTIS #AD-653 137, July 1960, 18 pp. plus 16 pp. appends., 16 refs.

Equations relating to the accretion and decay of sea ice to standard meteorological data are derived empirically from observations at 5 stations (Albert, Eureka, Isachsen, Mould Bay, and Resolute) with varying periods of record from 1947-1957. The equations differ from existing formulas in that they are differential in nature, to permit calculation of ice growth by increments, and contain a separate term allowing for variations in snow-cover depths. The use of the formulas requires only a knowledge of air temperatures and snow depths. A good correlation is found between the decrease in ice thickness and accumulated degree days above -1.8°C. The location of each station, the names of the surrounding water bodies, and the approximate water depths where ice thickness measurements were made are listed in Appendix A; the techniques used in the measurements are described in Appendix B; data on observed ice thickness are tabulated in Appendix C; and accumulated degree days of frost and average snow depths for 20-cm increments of ice growth are tabulated in Appendix D.

Bilello, M.A., **Surface temperatures and growth of sea ice**, NTIS #AD-653 136, January 1961, 10 pp., 8 refs.

Concurrent measurements of ice growth and ice-surface temperatures made at Eureka (N.W.T.) during the 2 seasons 1949-51 were utilized to compute a composite numerical value for 3 physical properties of sea ice-thermal conductivity k, latent heat of fusion L, and density rho combined as k/L x rho. Values for this expression were found to: (1) increase from approximately 4.7-7.0/100,000 during ice growth from 0.6-1.0 m thickness (Nov. 6-Dec. 22); (2) range from 7.0-8.0/100,000 during ice growth from 1.1-1.3 m thickness (Jan. 20-Feb. 10); (3) decrease slightly during the remaining growth period. These variations may be considered as due to changes in the effective conductivity related to physical changes and brine distribution in sea ice. A near linear relationship was found between mean daily ice accretion and sea-ice temp gradient.

Calkins, D.J. and Muller, A., **Frazil ice formation in turbulent flow**, *IAHR Symposium on Ice Problems*, Luled, Sweden, 7-9 August 1978, Proceedings, Part 2, International Association for Hydraulic Research, 1978, pp. 219-234, 9 refs.

To study ice nucleation and heat transfer, frazil ice was produced experimentally under controlled conditions. Turbulence was generated by a moving grid in a turbulence jar, where water could be cooled below the freezing point. Frazil was observed by means of a schlieren system and the number of ice particles was counted on photographs. No frazil ice formed, regardless of turbulence and foreign material, unless the water was seeded with ice nuclei. The number of particles grew during the experiment; the growth rate increased with greater supercooling and higher velocity of the grid. This indicates a multiplication process induced by secondary nucleation. The heat transfer per particle normalized with supercooling, and size of the particles was constant in all experiments within the accuracy of measurement. From these observations, it can be concluded that the total ice production is predictable if the heat transfer per particle can be estimated from turbulence data and if the number of particles can be calculated. A nucleation theory is, however, not available and is regarded as the crucial question.

Campbell, W.J., **On the steady-state flow of ice**, University of Washington, Seattle, Scientific report, 1222D2 USGRDR, July 1964, 2 pp.

The purpose of this paper is to create a model in which the ice and ocean are viewed as a dynamic unit and in which the gradient currents and internal ice stresses are included. Also, this paper is concerned with the solution of such a model.

Campbell, W.J., **The wind-driven circulation of ice and water in a polar ocean**, *Journal of Geophysical Research*, Vol. 70, 1965, pp. 3279-3301.

A steady-state theory for the circulation of a wind-driven, baroclinic, ice-covered ocean is presented. The ice is considered to flow under the action of five forces: the air stress, the water stress, the stress transmitted through the ice pack, the Coriolis force, and the pressure gradient force due to the tilting of the sea surface. Prandtl-type boundary layers are assumed at both ice surfaces. The ice is treated as a film of highly viscous fluid, composed of ice floes that act as fluid elements having rigid upper and lower surfaces characterized by roughness parameters. The theory is applied to the Arctic Ocean, where the plan approximation cannot be made, so the actual variation of the

Coriolis parameter with latitude is considered. A non-analytical stress field deduced from the field of mean sea-level pressure is used for the numerical integration of the equations. The solutions for the ice circulation show an anticyclonic cell centered in the Beaufort Sea with a broad stream running from the Asian coast across the pole to Greenland. All solutions show an anticyclonic gyral in the surface waters on the Pacific side of the ocean, and it is theorized that an ice eddy viscosity as high as $3.0 \times 10^{12}$ cm$^2$ sec$^{-1}$ is necessary in order for the gyral to occupy its observed position.

Clifford, W.F. and Erman, R.J., **Experimental determination of melting rates of ice moving in seawater**. Master's Thesis, Naval Postgraduate School, Monterey, California, #251450, March 1979, 220 pp.

Large, fresh-water ice blocks (0.5 m x 1.25 x 5 m) were towed in Monterey Bay at speeds in range from 0.7 to 1.2 knots. Experimental objectives included measuring gross regression rates of ice surfaces, wake temperature, turbulent thermal boundary layer, ice interior temperature profile, and observation of shape changes over the melting period. The research was conducted over a period from October 1977 to January 1979. Measured regression rates at several points on the ice blocks were compared to theoretical predictions using a turbulent flow ice ablation model developed by Owen Griffin of the Naval Research Lab. Griffin's model predicted a regression rate of 280 mm/hr compared with the measured value of 260 mm/hr at a selected point. Temperature profiles in the ice interior and ice-water boundary layer were used in a one-dimensional energy balance across the melting interface. Ice ripples, observed on all ice block tests, are important for both heat transfer and drag considerations. Wavelengths of the ripples were measured and the average wavelength was 6.1 in. compared to the theoretical average predicted by Tatinclaux and Kennedy of 5.8 in. for a selected experiment.

Colony, R., **Simulation of Arctic Sea ice dynamics**. *AIDJEX Bulletin*, No. 31, University of Washington, Seattle, March 1976, pp. 151-168, refs.

A mathematical model of large-scale sea ice dynamics has been formulated, which provides a theoretical background for the AIDJEX 1975-1976 experiment in the Beaufort Sea. Governing differential equations are developed to predict ice motion, the distribution of ice thicknesses, and internal ice stress. The motion is induced by synoptic-scale air and ocean flow in the Beaufort Sea during the 1975-1976 experiment. The data from a network of drifting data buoys and manned drifting ice stations are used in the model formulation and in the verification of analysis. The finite difference approximations of the differential equations and the computational algorithm are outlined. Results of model calculations will be compared with data acquired by airborne and satellite-based sensors.

Colony, R., Maykut, G.A., Rothrock, D.A., and Thorndike, A.S., **The thickness distribution of sea ice**, *Journal of Geophysical Research*, Vol. 80, No. 33, 20 November 1975, pp. 4501-4513.

The polar oceans contain sea ice of many thicknesses ranging from open water to thick pressure ridges. Since many of the physical properties of the ice depend upon its thickness, it is natural to expect its large-scale geophysical properties to depend on the relative abundance of the various ice types. The ice pack is treated as a mixture whose constituents are determined by their thickness and whose composition is determined by the area covered by each constituent. A dimensionless function g(h), the ice thickness distribution is defined such that g(h)dh is the fraction of a given area covered by ice of thickness greater than h but less than h + dh. A theory is developed to explain how the ice thickness distribution changes in response to thermal and mechanical forcing. The theory models the changes in thickness due to melting and freezing and the rearrangement of existing ice for form leads and pressure ridges. In its present form the model assumes as inputs a growth rate function and the velocity field of the ice pack. The model is tested using strain data derived from the positions of three simultaneous manned drifting stations in the central Arctic during the periods 1962-1964 and growth rates inferred from climatological heat flux averages. The results are compared with estimates of g based on submarine measurements of ice thickness.

Dogoslovskii, P.A., **Ice regime of hydroelectric station pipelines**, NTIS #ADA-038 302, February 1977, 133 pp., 28 refs.

Conditions favorable for ice formation in water supply lines are analyzed. Methods of calculating the probable ice thickness within pipes are suggested. The thermal regime of water flowing in a pipe, its dependence on outer and inner factors, and measures for the prevention of ice damage are discussed. Special attention was paid to the problem of ice formation in water turbines.

Doronin, Y.P., Smetannikova, A.V., and Zhukovskaya, N.A., **Testing a numerical model of spring-summer redistribution of sea ice**, *AIDJEX Bulletin*, No. 16, Seattle, Washington, 1972, pp. 35-45.

A mathematical model for computing ice thickness and ice drift, which takes into account ice compaction, is outlined with the aide of the relevant equations. The model deals with steady-state drift produced by tangential wind stresses (wind drag). The interaction between ice floes is introduced in the form of viscous drag (R). The general balance equation of the forces acting upon ice, F.SUB 1. + F.SUB 2. + C + R = 0, contains the terms for air drag (F. SUB 1.), water drag (F.SUB 2.), the Coriolis force (C), and the drag associated with the interaction of floes (R). The equations for these terms and the equation for ice thickness are

presented. The computer program for the ice compaction and drift at the point of a regular grid for a given region in the Arctic basin is described, and the results of computations are presented and compared with actual data. The validity of the numerical model in analyzing the formation of ice cover in the spring and summer, as a result of the combined effect of thermal and dynamic factors, is demonstrated.

Dubrovin, L.T. and Savatiuqin, L.M., **Fast ice dynamics in the Mirny area**, NTIS #AD-748 399, June 1972, 6 pp., 6 refs.

The conditions for formation and the morphological characteristics of fast ice in the Mirny region from March 21 to April 25, 1966, are described. Charts for the fast ice for several years show that deformations and fractures have occurred at the same places every year, seemingly caused by constant conditions of the same origin. A classification is given of tidal, wave, deflection, and horizontal tearing fractures caused by sea level fluctuations, sea swell, snow accumulation, glacier flow, icebergs, islands, and the coastal contour. The need for precise data on the fast-ice dynamics during ship unloading and cargo transportation from ship to base is discussed.

Dunbar, M., **Ice regime and ice transport in Nares Strait**, Defence Research Establishment, Ottawa, Report No. DREO-TN-72-31, Summaries in French and Russian, *Arctic*, Vol. 26, No. 4, December 1973, pp. 283-291.

In order to assess the part played by ice export through the Canadian Arctic Archipelago in the heat budget of the Arctic Ocean, one of the factors that must be known is the length of time per year that the channels are sealed by fast ice. To establish this for Nares Strait a series of flights was undertaken through the winters of 1970-71 and 1971-72. The resulting observations, combined with a search of historical records, suggest that the date of consolidation of ice in this channel tends to be late. A tentative calculation of annual export leads to the conclusion that the contribution of the Canadian channels may be greater than has been supposed.

Firestone, M.A. (comp.), **Computer programs in marine science**, United States National Oceanic and Atmospheric Administration, Washington, D.C., Environmental Data Service, Key to Oceanographic Records Documentation No. 5, April 1976, 225 pp.

This updating of a similar publication of NODC in 1970 contains abstracts of 700 computer programs supplied by nearly 80 institutions in ten countries. An extensive keywork (or phrase) index and a language (computer) index are appended. Among the 22 categories, those of special interest are physical oceanography, pollution, currents, tides, waves, air-sea interaction and budget, ice sound, and data reduction. More specific subjects covered are programs for computation of radiometer or pyranometer data, ocean climatology analysis, hurricane heat potential model, atmospheric water content model, wind from ship observations, Mie scattering, wind stress, solar radiation conversion, cloud cover, and daily sea temperatures, prediction models, and many programs for computation or interpolation of ocean station or ship report data.

Foster, T.D., **An analysis of the cabbeling instability in sea water**, *Journal of Physical Oceanography*, Vol. 2, No. 3, July 1972, pp. 294-301.

Due to the nonlinear equation of state of sea water it is possible for the mixture of two parcels of sea water with the same density but different temperatures and salinities to have density greater than that of the constituent parcels. This phenomenon is sometimes called cabbeling. In the deep parts of the Weddell Sea the surface water is usually colder and less saline than the underlying deep water. In winter the salinity of the surface water can increase due to sea ice formation, and then mixtures of surface water and deep water may become denser than the underlying deep water. An instability can develop, which may transport the heavier mixed water through the deep water and contribute to the formation of Antartcic bottom water.

Foster, T.D., **Heat exchange in the upper Arctic Ocean**,*AIDJEX Bulletin*,No. 28, University of Washington, Seattle, 1975, pp. 151-166.

Two numerical models for the upper Arctic Ocean were developed. The first used a pseudo two-dimensional hydrodynamic model to follow the development of convection under a growing ice sheet. The second model exploits the conclusions from the first and uses the Zubov method to model the convection while stepping the temperature and salinity fields forward with the one-dimensional diffusion equations.

Gerson, D.J. and Perchal, R.J., **Sea ice growth in potential Arctic minefield areas**, Naval Oceanographic Office, Washington, D.C., Report No. N00-TN-7700-11-73, 16 April 1973, 19 pp.

An empirical method of determining the date of initial ice formation using daily air temperatures is described and applied to Zubov's and Kolesnikov's equations to determine day-to-day growth in ice thickness. Several methods are also used to estimate ice drift and disintegration.

Gerson, D.J. and Simpson, L.S., **Wind drift of sea ice: a supplement to the Naval Oceanographic Office numerical ice forecasting system**, Naval Oceanographic Office, Washington, D.C., Report No. N00-RP-8-S, September 1976, 28 pp.

The numerical ice prediction system described in RP 8 has been in use since 1971. Its outputs, however, have been related only to ice growth, not ice drift. In

addition, the system now provides an output of daily ice drift at 62 arctic stations. Drift is calculated as a function of wind stress, water stress, and Coriolis force. The computer output is sufficiently accurate for the drift in the locality of the station whose wind observations were input to the model. However, more recent research indicates that for greater accuracy and for computations of divergence and convergence, interaction between floes must be considered.

Gow, A.J., Hibler, W.D., III, Kovacs, A., Mock, S.J., Tucker, W.B., and Weeks, W.F., **Studies of the movement of coastal sea ice near Prudhoe Bay, Alaska**, *Journal of Glaciology*, Vol. 19, No. 81, 1977, pp. 533-546.

During March-May 1976, a combination of laser and radar ranging systems was used to study the motion of both the fast ice and the pack ice near Narwahl and Cross Islands, two barrier islands located 16 and 21 km offshore in the vicinity of Prudhoe Bay, Alaska. Laser measurements of targets on the fast ice near Narwahl Island indicate small net displacements of approximately 1 m over the period of study (71 d) with short-term displacements of up to 40 cm occurring over 3 d periods. The main motion was outward normal to the coast and was believed to be the result of thermal expansion of the ice. The radar records of fast ice sites farther offshore show a systematic increase in the standard deviation of the displacements as measured parallel to the coast, reaching a value of 6.6 m at 31 km. The farthest fast-ice sites show short-term displacements of up to 12 m. There are also trends in the records that are believed to be the result of the general warming of the fast ice with time. Radar targets located on the pack ice showed large short-term displacements (up to 2.7 km), but negligible net ice drift along the coast. There was no significant correlation between the movement of the pack and the local wind, suggesting that coastal ice prediction models can only succeed if handled as part of a regional model that incorporates stress transfer through the pack. The apparent fast-ice-pack-ice boundary in the study was located in 30-35 m of water.

Hall, R.T., Maykut, G.A., and Rothrock, D.A., **Sea ice modelling: its testing with LANDSAT and potential use in FGGE**, *Symposium on Meteorological Observations from Space: Their Contribution to the First GARP Global Experiment, Proceedings*, Philadelphia, Pennsylvania, 8-10 June 1976, pp. 104-109, refs.

Major components of the AIDJEX (Arctic Ice Dynamics Joint Experiment) ice model are described. This dynamic-thermodynamic model consists of a thickness distribution model, a momentum equation, and a stress-strain law for pack ice. The use of LANDSAT data on ice cover-ice thickness distribution and deformation to test assumptions contained in the model is presented, as well as telemetered data obtained during the FGGE to estimate regional rates of heat and mass exchange over the polar ocean.

Hansen, R. and Linell, K., **Strength and uses of fresh and salt water ice**, NTIS #AD-661 627, January 1949, 36 pp., 15 refs.

The report is an analysis of the structural usefulness of fresh and salt water ice in the Arctic. The uses of both sea ice and fresh water ice as an aid to transportation are given. Ranges of ice strength test results are given in tables.

Hibler, W.D., III, **A viscous sea ice law as a stochastic average of plasticity**, *Journal of Geophysical Research*, Vol. 82, No. 27, 20 September 1977, pp. 3932-3938, refs.

The applicability of viscous constitutive laws to sea ice on the geophysical scale recently has been questioned, because the local characteristics of sea ice deformation appear to be plastic. To provide a more fundamental physical basis for a viscous law, this paper demonstrates that if time and/or length scales are chosen large enough, then stochastic variations in sea ice deformation rates can cause the average stress-strain rate relationship on these scales to take on viscous characteristics, even though the nonaveraged relationship is plastic in character. In particular, when a 2-dimensional plastic model with an elliptical yield curve is used, the stochastically averaged stress-strain rate relationship takes the form of a viscous law with a pressure term: (rij)=2g(eij)+((f-g)(ekk)-P)d ij, where angle brackets denote averages and where g=f. Examination of actual sea ice deformation time series and deformation rates simulated by red noise suggests that minimal time scales for the application of such averaging arguments can be as short as 1 d. The calculations also yield an empirical ratio between the plastic strength of the ice, P*, and the viscous parameters: g/P*ff/P*4.0x106 s. The viscous law, with the inclusion of a bulk viscosity and pressure term, is applicable to sea ice modeling.

Hibler, W.D., III, **Differential sea-ice drift, II: comparison of mesoscale strain measurements to linear drift theory predictions**, *Journal of Glaciology*, Vol. 13, No. 69, 1974, pp. 457-471, 18 refs., In English with French and German summaries.

A comparison of mesoscale strain measurements with the atmospheric pressure field and the wind velocity field indicate that the ice divergence rate and vorticity follow the local pressure and wind divergence with significant correlation. For low atmospheric pressures and converging winds the divergence rate was found to be negative with the vorticity being counterclockwise. The inverse behavior was observed for high pressures and diverging winds. This behavior was shown to agree with predictions based upon the infinite boundary solution of a linearized drift theory in the absence of gradient current effects and using the

constitutive law proposed by Glen (1970) for pack ice. The best least-squares values of bulk and shear viscosity were derived. Using typical divergence rates these derived values yield compressive stresses that are similar to values suggested by the Parmerter and Coon (1972) ridge model. In general, the infinite boundary solution of the linear drift equation indicates that in a low-pressure region that is reasonably localized in space, the ice would be expected to converge for high compactness (winter) and diverge for low compactness (summer). Calculations were also carried out using a more general linear visco-elastic constitutive law that includes memory effects and a generalized Hooke's law as well as the Glen law as special cases. A best fit of this more general calculation with strain measurements indicates overall a better agreement with viscous behavior than with elastic behavior, with the frequency behavior of the estimated "viscosities" similar to the Glen law behavior at temporal frequencies.

Hibler, W.D., III, and Tucker, W.B., **Examination of the viscous wind-driven circulation of the Arctic ice cover over a two year period,** *AIDJEX Bulletin*, No. 37, September 1977, pp. 95-133, 27 refs.

A detailed re-examination of the viscous approach is made by comparing predicted with observed ice drift in the Arctic basin over a two-year period employing a viscous constitutive law having both bulk and shear viscosities. Numerical drift calculations for the Arctic Basin are carried out at 4-day intervals over a two-year period employing periodic boundary conditions. Drift predictions are compared with the observed drift of three contemporaneous drifting stations with reasonable agreement. The largest errors are found to occur in late summer, and may be due to nonsteady current effects. Boundary value calculations show that reduction of the shear viscosity (while still maintaining a large bulk viscosity) reduces the excessive stiffening often found in viscous models while still maintaining substantial changes in drift direction due to boundaries. Sensitivity studies show steady current effects to be small for drift rates over tens of days but not negligible for cumulative drift over years.

Hibler, W.D., III, **Seasonal variations in apparent sea ice viscosity on the geophysical scale**, *Geophysical Research Letters*, Vol. 4, No. 2, February 1977, pp. 87-90, 12 refs.

Using available atmospheric pressure and ocean current data and estimating non-local stress transferral through the ice cover by employing a viscous drift model in the infinite boundary limit, predicted dirft rates for one Russian and two U.S. drifting stations are made over the time period May 1962 to April 1964. The viscosity values giving the best fit between observed and predicted values show a pronounced winter increase that correlates well with the ice growth rate. Physically, this suggests that ice drift rates (for a given wind field) tend to decrease in winter because of increased stress transferral through the ice cover. An empirical linear relationship between viscosity and ice growth rate is derived that yields predictions in reasonable agreement with both long- (yearly) and short-term (monthly) observed drift rates.

Hunkins, K., **Ekman drift in the Arctic Ocean,** *Deep Sea Research*, Vol. 19, 1966, pp. 607-620.

Current observations from a drifting ice floe on the central Arctic Ocean give clear evidence of a clockwise spiral structure in the upper layers. The data for steady conditions show a boundary layer just beneath the ice and an Ekman spiral layer below it. The depth of frictional influence is 18 m for winds of 4 m/sec. This is apparently the first detailed confirmation of the Ekman spiral in deep waters.

Jacobs, J.D., **Fast ice characteristics, with special reference to the eastern Canadian Arctic,** *Polar Record*, Vol. 17, No. 110, Cambridge, England, May 1975, pp. 521-536, refs.

A general discussion of sea ice, with emphasis on pack ice, has been presented recently by Wittman and Burkhart (1973), but another aspect of the sea ice regime deserving special attention is the landfast or fast ice, i.e., that part of the sea ice that remains attached to the shore. This paper attempts to provide a broad picture of fast ice characteristics in the context of field experience in the eastern Canadian Arctic. Fast ice in the lower latitudes generally consists of young and first-year ice, but included increasing proportions of multi-year ice in the northern Canadian Arctic islands. A figure shows the extent of fast ice in the Canadian Arctic (not including Hudson Bay). Maps for the eastern coast of Baffin Island show that the fast ice edge approximates the 180-m (100-fathom) line, which is about 70-km offshore in Home Bay, and overlies even deeper waters among the islands farther north; however, no general rule of a depth-controlled fast ice margin can be made for the Arctic as a whole. The thickness of predominantly first-year fast ice varies from one to two meters; it is thickest in early spring. The growth, ablation, and break-up of fast ice are discussed quantitatively. The physical processes relative to sea-ice-atmosphere interaction in summer are illustrated in a diagram. The use of physical prediction equations presents problems resulting from local variability of conditions and incomplete observational data.

Kan, S.I., and Tyunrev, Y.A., **Temperature field of the ocean and the prediction of ice phenomena in seas**, USSR Gidrometeorologicheskiy Nauchno-Issledovatel'skiy Tsentr SSR, Leningrad, *Trudy*, No. 83. 1971, pp. 87-94.

The influence of the summer (and part of the spring and fall) temperature field of the ocean upon ice

conditions on the Azov, Caspian, and Okhotsk seas in the following winter is investigated. The elements of the ice regime, such as ice amount, thickness of ice, time of appearance of ice, and duration of ice cover are also examined. Regression equations are developed for the mean ice amount of the Azov and Caspian seas in Jan.-Feb. as a function of total water temperature anomaly in Aug. in the Atlantic Ocean for the weather ships, A, B, C, D, E, and M; and a regression equation for the ice amount in the Okhotsk Sea in Dec. as a function of expansion coefficients of water temperature anomalies in preceding months in a Chebyskev series. The distribution of water temperature in the ocean as early as August enables prediction of some ice phenomena in winter, in particular their start.

Kovacs, A. and Weeks, W.F., **Dynamics of near shore ice**, *Environmental Assessment of the Alaskan Continental Shelf*, Vol. XVI, Principal investigators' report for the year ending March 1977, Environmental Research Laboratories, Boulder, Colorado, 1977, pp. 151-163.

This paper deals with the study of near-shore ice divided into 3 programs of: 1. Narwhal Island, 2. Bering Strait Program, 3. Remote Sensing Program.

Kovacs, A., **Grounded ice in the fast ice zone along the Beaufort Sea coast of Alaska**, United States Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Report No. 76-32, September 1976, 21 pp., refs.

Four large, grounded, multi-year shear ridge formations were found in the grounded ice subzone of the fast ice zone near the Harrison Bay-Prudhoe Bay area of Alaska. A 166-m-long cross section of one of these formations was obtained by leveling and sonar measurements. These measurements revealed that the maximum ridge height was 12.6 m and that the formation was grounded in 17-18 m of water. The salinity, temperature, brine volume, and density of the ice were determined on samples obtained by coring. The physical characteristics of the formations as observed in satellite, SLAR, and aerial imagery indicate that these formations have not moved between the time of their formation in the fall of 1974 and August of 1976. Evidence of significant aeolian debris discoloring the ice is discussed.

Krutiskin, B.A., **Pecularities of ice formation in the Arctic Seas**, *Ice Forecasting Techniques for the Arctic Seas*, New Delhi: Amerind Publ. Co. Pvt. Ltd., 1976, pp. 108-121, refs.

The reasons for space-time variations in the dates of ice formation in the Arctic seas are investigated by means of dispersion analysis. They are explained by known assumptions regarding different characteristics of warming and cooling of shallow water and deep-water sectors of the seas in the presence and absence of heat advection by sea currents and river inflow. A method for short-term prediction of times of ice formation in the Arctic seas is developed. It involves the use of equations for estimating the mean time of ice formation in the Arctic seas in a given year, as a function of mean compactness of ice of all seas and mean temperature of the atmosphere according to data of polar stations in the first 10 days of Sept., and equations for calculating the times of ice formation in regions where old ice exists and for deep regions where no ice exists. In the case of regions of old ice, the time of ice formation is a function of average time of several years and the mean compactness of ice for all seas; and in the case of deep regions without old ice, it is a function of the average time of several years, distance to the ice edge, thickness of the active layer of the sea, and temperature of the atmosphere in the third ten days of September.

Langleben, M.P., **Decay of an annual cover of sea ice**, *Journal of Glaciology*, Vol. 11, No. 63, Cambridge, England, 1972, pp. 337-344.

In his now classic book *L'dy Arktiki (Arctic ice)*, Zubov discussed the melting of sea ice during the Arctic summer by thermal interaction with the surrounding water, and derived an expression that indicates that the proportion of open water increases exponentially with time until total ice-free conditions result. His equation predicts that the time required for complete decay of the ice cover after initial breakup is greater than one month and, more likely, as long as two months, for representative values of incident short-wave radiation and initial ice thickness upon breakup. It is unlikely that above-freezing temperatures persist for this length of time. To explain the observed complete disintegration of the annual ice cover in many sheltered areas of the Arctic, a modified model of the thermal decay process has been introduced. This model takes into account the influence of radiation absorbed by the ice, which was not included in the Zubov formulation. Considerable reduction in the time required for complete decay, generally about a factor of 2 if an albedo of 0.4 is assumed for the ice surface, is obtained.

Lofgren, G. and Weeks, W.F., **Effect of growth parameters on substructure spacing in NaCl ice crystals**, NTIS #AD-687 280, January 1969, 17 pp., 32 refs.

The effect of growth velocity $v$ and solute concentration $C$ on the cellular substructure that develops in NaCl ice is studied in the range .003 to .00003 cm/sec and 1 to 100 percent respectively. The substructure is the result of the formation of a constitutionally supercooled zone in the liquid ahead of the advancing interface. Unidirectional freezing runs were made by placing a cold plate in contact with the top of the solution and using cold-plate temperatures of -20 and -70°C. The growth velocities were deter-

mined from a least-squares fit of the growth data to a power series. The average spacings between neighboring substructures were measured from photomicrographs of precisely located thin sections.

Maykut, G.A. and Untersteiner, N., **Arctic sea ice,** *Naval Research Reviews,* May 1969, pp. 12-23. University of Washington, Seattle, Department of Atmospheric Sciences, Technical Report No. TR-3.

The paper presents the results of a thermodynamic model that described growth and decay of sea ice. External forcing functions are incoming solar and atmospheric radiation, turbulent fluxes in the air and water boundary layers, and snow fall. Calculated are snow or ice surface temperature, internal temperatures, and thickness. Contemporary estimates of the forcing functions held excellent agreement with empirical data. The consequences of variations in the water exchange between the Arctic Ocean and the Atlantic, and of changes in the radiation regime are discussed in the light of possible artificial removal of the ice.

Maykut, G.A., **Energy exchange over young sea ice in the central Arctic**, *AIDJEX Bulletin,* No. 31, University of Washington, Seattle, March 1976, pp. 45-74, refs.

A simple model of heat transport in young sea ice is combined with climatological data on air temperatures and incoming radiation fluxes to predict how each component of the local heat balance in the central Arctic is affected by the rapid growth of ice in leads. Results indicate that the net heat input to the atmosphere over 0-40 cm of ice during the cold months is between one and two orders of magnitude larger than that over perennial ice. Once the ice exceeds about 100 cm in thickness, there is little change in any of the heat fluxes as the ice thickens. Although both the amount of absorbed short-wave radiation and the emitted long-wave radiation depend upon ice thickness, the turbulent fluxes undergo the largest changes. The effects of a snow cover and variations in boundary layer temperatures are also examined. It is concluded that, with the present ice thickness distribution in the Central Arctic, total heat input to the atmospheric boundary layer from regions of young ice is equal to or greater than that from regions of open water or thick ice.

Maykut, G.A. and Untersteiner, N., **Numerical prediction of the thermodynamic response of Arctic sea ice to environmental changes**, Rand Corporation, Santa Monica, California, Report No. RM-6093-PR, November 1969, 184 pp.

A description is given of a one-dimensional model of Arctic sea ice. The inputs are: albedo, incoming radiation, turbulent fluxes, oceanic heat flux, ice salinity, and snow accumulation. Given an arbitrary initial ice temperature field and ice thickness, the model predicts the changes in these wrought by specified environmental parameters. Annual variations in temperature and thickness are followed year by year until the pattern is stable, i.e., until either the ice disappears or the annual sequence of growth and depletion is repeated and unchanged. Values predicted (using inputs based on the present climate) agree closely with field observations. Tables for 28 specified cases and annual charts for 25 are presented. In addition to showing annual growth and depletion of ice under normal and anomalous climates, results show mechanisms by which environmental conditions affect the ice.

Maykut, G.A. and Untersteiner, N., **Some results from a time-dependent thermodynamic model of sea ice**, *Journal of Geophysical Research,* Vol. 76, No. 6, 20 February 1971, pp. 1550-1575.

A one-dimensional thermodynamic model of sea ice is presented that includes the effects of snow cover, ice salinity, and internal heating due to penetration of solar radiation. Surface-energy balances determine rates of ablation and accretion; diffusion equations govern heat transport within the ice and snow. The incoming radiative and turbulent fluxes, oceanic heat flux, ice salinity, snow accumulation, and surface albedo are specified as functions of time. Starting from an arbitrary initial condition, the model is integrated numerically until annual equilibrium patterns of temperature and thickness are achieved. The model is applied to the central Arctic.

Mellor, M., **Promoting the decay of sea ice,** *Arctic,* Vol. 16, No. 2, June 1963, p. 142.

Studies made on the flooded runway at McMurdo Sound show that the decay of sea-ice by hosing the ice surface with normal sea-water in the spring is possible. Surface salinity increases 20 to 30 percent, thus allowing a higher absorption of incident solar radiation. The net results of heat transfer processes reduced the treated ice to a low-strength, porous condition early in the season. Hosing techniques may have application to free-flooding operations for thickening runways on sea-ice.

Milne, A.R., **The transition from moving to fast ice in western Viscount Melville Sound,** *Arctic,* Vol. 23, No. 1, March 1970, pp. 45-46, Defence Research Establishment, Pacific, Victoria, British Columbia, Report No. 70-1.

An unexpected result of the recording of underwater noise under sea-ice is the ability to detect the difference in character of the noise generated by ice in motion in relation to the noise generated under shorefast ice. The detection of motion was easily made by observing the hourly samples of underwater noise recorded by a remote instrument package (RIP). One RIP was installed in the sea bottom south of Melville Island in August 1967 and was recovered one year later. A sample strip-chart record of the change of

underwater noise-power with time in the 150-300 Hz frequency band is shown.

National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, *Environmental Assessment of the Alaskan Continental Shelf*, Vol. XV, Annual Report, 1 April 1976 - 31 March 1977, 678 pp., Prepared in cooperation with the Bureau of Land Management, Washington, D.C.

Reports containing baseline studies are compiled in this annual report. They are intended to serve as markers or as points of departure from which to assess the potential environmental impact that might result from resources development on the Alaskan Continental Shelf. This compilation contains the following studies: Mechanics of origin of pressure ridges, shear ridges, and hummock fields in landfast ice; Morphology of Beaufort, Chukchi, and Bering Seas near shore ice conditions by means of satellite and aerial remote sensing; Experimental measurements of sea ice failure stresses near grounded structures; Beaufort Sea, Chukchi Sea, and Bering Strait baseline ice study; Development of hardware and procedures for in situ measurement of creep in sea ice; Operation of an Alaskan facility for applications of remote-sensing data to OCS studies; Circulation and water masses in the Gulf of Alaska; and Marine climatology of the Gulf of Alaska, the Bering and Beaufort Seas.

National Oceanic and Atmospheric Administration, Outer Continental Shelf Environmental Assessment Program, *Environmental Assessment of the Alaskan Continental Shelf*, Vol. II, Quarterly Reports of Principal Investigators, April-June 1977, October 1977, 943 pp., Prepared in cooperation with the Bureau of Land Management, Washington, D.C.

Reports containing baseline studies are compiled in this quarterly report. They are intended to serve as markers or as points of departure from which to assess the potential environmental impact that might result from petroleum resources development and transport on the outer continental shelf of Alaska. The reports are grouped in the following categories: Transport, hazards, and data management. (Portions of this document are not fully legible.)

Nazintsev, Y.L., **Estimating the lateral melting of drift ice**, *AIDJEX Bulletin*, No. 17, December 1972, pp. 71-76.

Observations of the lateral melting of drift ice were made on the Severnyi Polyus-13 drifting station during 1966. During the observations at the beginning of the melting period, a long narrow lane formed along the break line in the ice and persisted through the summer until the autumn cold. Measurement of the water temperature and salinity fields showed that the melt-water running off the ice spreads over the surface of the lane, forming a relatively thin (0.5 to 1.0 m) layer of saline water with a sharp temperature and salinity discontinuity relative to the underlying sea water. The temperature field also showed small horizontal gradients, with the temperature decreasing from midlane to the ice edge. The gradients were steepest near the ice. This structure of the temperature field accounts for the nonuniform vertical melting of the ice. The lateral melting within the low salinity layer above the discontinuity layer is double the melting at the bottom of the ice floe. The contribution of lateral ice melting rapidly increases as floe dimensions drop to a few tens of meters. Bottom melting increases significantly only at the very edge of the ice. Most of the heat supplied by the lane water is used up in lateral melting and does not contribute much to the melting of the bottom surface of ice. Only 10% of the heat absorbed by lane water from air was used in lateral melting of ice. While the fraction of heat expended in lateral ice melting diminishes with increasing lane width, the rate of lateral melting naturally increases. The rate of lateral ice melting is correlated with the changes in the lane width within the warm top surface layer of water in the lane; the correlation may break down below the temperature discontinuity.

Nazintsev, Y.L., **Melting of hummock ice**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-TL401, August 1973, 12 pp., Draft translation of Arkticheskii i Antarkticheskii Nauchn-Issledovatelskii Institut. *Trudy* (USSR), Vol. 300, 1971, pp. 92-100.

The summer thawing of sea ice is one of the main elements in ice forecasting. The polar stations in the Arctic have accumulated extensive data on the thawing and disintegration of ice. However, almost all of the data is related to the smooth surface of an ice cover rather than to hummocks. At the same time, the hummocking zones occupy such an appreciable area that in the continuous and concentrated ice formations, they comprise the main obstacle in the movement of vessels. In this connection, an estimation of the thawing and weakening of ice in the hummocks is of practical interest. Results obtained from measurements in the ice accumulations in the many years' field work of the North-Pole 13 station in 1966 are listed. A simple system for calculating the ice mass destroyed by thawing in the hummocks is suggested.

Neraila, V.R., **Ice motion in the Beaufort Sea**, Canadian Marine Sciences Directorate, Ottawa, Manuscript Report Series No. 43, 1977, pp. 259-276, refs.

Accurate forecasting of ice drift would be a useful guide for the proposed oil drilling operations in the Beaufort Sea. An attempt is made to describe a steady-state theory of ice drift based on a balance of air-ice drag, water-ice drag, and Coriolis force. Air-ice drag is computed by assuming that the velocity of air is much greater than the velocity of ice. Water current

contribution to ice motion is incorporated by using Ekman's relationship between water current and wind velocity. Case studies of ice motion in the Beaufort Sea area are presented. Methods of computing forward and backward, two-dimensional horizontal trajectories of an ice particle originating at any arbitrary point are discussed.

Nikolayeva, A.Y., **Results of calculations of ice zones of varying age in the Arctic seas**, Leningrad, Arkticheskiy i Antarkticheskiy Nauchno-Issledovatel'skiy Institut, *Trudy*, Vol. 320, 1976, pp. 121-142, refs.

The method of calculating the distribution of ice in the Arctic seas in the fall-winter period involved the use of monthly mean atmospheric pressure maps, from which the displacement of randomly selected points in the boundary of fast ice for Jan.-May, Feb.-May, March-May, April-May, and May were calculated. Lines, drawn at the ends of resulting vectors of drift for each of the periods, gave the position of ice zones at the end of May, formed in Jan., Feb., etc., until May. The ice thickness was calculated at the boundary of these zones. In a similar manner, the displacement of the boundary of inclusion and predominance of old (remaining) ice for Oct.-May was calculated. The drift of ice was calculated by considering the mean position of the boundary of fast ice in the winter period and of the ice edge at the end of Sept. This method yielded a positive result of these areas: southwestern part of the Kara Sea, the Laptev Sea, the western part of the East Siberian Sea, and the Chukchi and Bering Seas. For these seas, the calculations make it possible to estimate the age and thickness of ice over the entire surface at any time of the winter period. The calculated areas of fall and two-year ice at the end of May in the southwest part of the Kara Sea can be used to forecast the ice state in the first half of the navigation period. The greater the calculated total area of this ice, the greater is the state of the ice. Over a 9 year period, the agreement of the sign of these anomalies was 100%. The total computed area of old and fall ice at the end of May, in the western part of the East Siberian Sea, can serve as a qualitative indicator of the ice state in the first half of August. This method permits an approximate calculation of the ice edge in the Chukchi Sea at the end of August from actual maps of monthly mean atmospheric pressure.

Omstedt, A. and Udin, I., **Sea Ice-75, Dynamical Report**, Swedish Meteorological and Hydrological Institute, Report No. REPT-16-8, 1976, 66 pp.

Field measurements on sea ice were carried out in the Bay of Bothnia during March 10-20, 1975. The forces and parameters in the equation of motion for sea ice have been studied on the mesoscale. Winds and currents were measured to calculate the wind and water stress, the ice mass distribution was studied, the tilting of the sea surface computed, temperatures at different ice types measured. From the data obtained and with classical boundary layer theory the forces in the equation of motion have been calculated and their balance studied. The results support the assumption made in a numerical ice forecasting model under development at the Swedish Meteorological and Hydrological Institute and the data obtained will be used for further development and improvements.

Parkinson, C.L., **A numerical simulation of the annual cycle of sea ice in the Arctic and Antarctic**, National Center for Atmospheric Research, Boulder, Colorado, Report No. NCAR-CT-46, 1978, 210 pp., Prepared in cooperation with Ohio State University.

This work describes the construction of and results from a numerical model simulating the yearly cycle of sea ice in both the northern and southern hemispheres. The model employs a rectangular grid with 200 km horizontal resolution, an 8-hr timestep, and four vertical layers--ice, snow, ocean, and atmosphere. Both thermodynamic and dynamic processes are incorporated, the thermodynamics being based on energy balances at the various interfaces and the dynamics being based on the following five stresses: wind stress, water stress, Coriolis force, internal ice resistance, and the stress from the tilt of the sea surface. Although the ice within a given grid square is of uniform thickness, each square also has a variable percentage of its area assumed ice-free. The model simulates a reasonable yearly cycle of sea ice thickness and extent in both the Arctic and Antarctic. The Antarctic ice grows from a minimum in March to a maximum in late August, while the Arctic ice expands from a September minimum to a March maximum. Overall, both thicknesses and concentrations are greater in the Arctic than in the Antarctic. Maps are presented of modeled thicknesses, concentrations, and velocities; and surface energy budgets are analyzed at selected grid points. (Copyright (c) Claire L. Parkinson, 1977.)

Parkinson, C.L. and Washington, W.M., **Large-scale numerical model of sea ice**, *Journal of Geophysical Research*, Vol. 84, No. C1, 20 January 1979, pp. 311-337, refs.

Work at the National Center for Atmospheric Research has resulted in the construction of a large-scale sea ice model capable of coupling with atmospheric and oceanic models of comparable resolution. The sea ice model itself simulates the yearly cycle of ice in both the northern and the southern hemispheres. Horizontally, the resolution is approximately 200 km, while vertically the model includes four layers-ice, snow, ocean, and atmosphere. Both thermodynamic and dynamic processes are incorporated, the thermodynamics being based upon energy balances at the various interfaces, and the dynamics being based upon the following five stresses: wind stress,

water stress, Coriolis force, internal ice resistance, and the stress from the tilt of the sea surface. Although the ice within a given grid square is of uniform thickness, each square also has a variable percentage of its area assumed ice free. The model results produce a reasonable yearly cycle of sea ice thickness and extent in both the Arctic and the Antarctic. The Arctic ice grows from a minimum in Sept., when the edge has retreated from most coastlines, to a maximum in March, when the ice has reached well into the Bering Sea, has blocked the north coast of Iceland, and has moved southward of the southernmost tip of Greenland. Maximum Arctic thicknesses are close to 4 m. In the Antarctic, the ice expands from a minimum in March to a maximum in late Aug., remaining close to the continent in the former month and extending northward of 60"S in the latter month. Maximum thicknesses are approximately 1.4 m. The distribution of modelled ice concentrations correctly reveals a more compact ice cover in the northern hemisphere than in the southern hemisphere. Modelled ice velocities obtain both the Beaufort Sea gyre and the transpolar drift stream in the Arctic summer, as well as the transpolar and East Greenland drift streams in the winter. In the Antarctic, simulated velocities reveal predominantly westerly motion north of 58"S, with smaller-scale cyclonic motions closer to the continent.

Pease, C.H., **Model for the seasonal ablation and accretion of Antarctic sea ice**, *AIDJEX Bulletin*, No. 29, University of Washington, Seattle, July 1975, pp. 151-172, refs.

Using information about mean climatic conditions in the Antarctic, a thermodynamic model is developed to predict mean sea ice extent and thickness as a function of time along a transect from 70 to 58"S at 115"E. One-dimensional heat budget calculations are made at two-degree intervals. The ice is treated simply, but the terms of the surface radiation balance are calculated explicitly from data of mean monthly atmospheric conditions. The ocean is treated in three ways that vary by the number of oceanic layers considered. The results compare favorably with mean observed extent, given the limitations of the calculations.

Rigby, F., **Theoretical calculations of internal wave drag on sea ice**, University of Washington, Seattle, Department of Atmospheric Sciences, Office of Naval Research, Arlington, Virginia, Report No. TR-26, 1974, 14 pp.

Because of the density stratification in the upper part of the Arctic Ocean, the movement of pressure ridge keels through the mixed layer can create internal waves in the vicinity of the pycnocline. These waves transport energy away from the keels and thereby generate drag on the ice. The study defines the conditions under which wave drag could contribute significantly to the total water stress. The development of internal waves downstream from a semielliptical keel is described by a simple two-dimensional, two-layer ocean model. Results calculated from the model show the dependence of wave drag on keel depth, current speed, depth of the upper layer, and density change across the interface between the layers. Comparison of the relative magnitudes of form drag and wave drag suggests that wave drag is not negligible near large keels when the current is flowing strongly.

Rothrock, D.A., **The steady drift of an incompressible Arctic ice cover**, *Journal of Geophysical Research*, Vol. 80, No. 3, 20 January 1975, pp. 387-397.

The steady drift of pack ice in an idealized arctic basin has been calculated by assuming that the ice is incompressible and inviscid. The momentum and continuity equations for the ice are solved for the velocity and the ice pressure. The divergence of velocity is assumed to be 0.33 x 10 to the minus 8th power/s. The boundary conditions require that no ice flows across coastal boundaries, but that ice flows out of the basin into the Greenland Sea and into the basin from the Kara Sea. The patterns of calculated velocities and vorticities are realistic, but their magnitudes are too high. The maximum calculated ice pressure of about 10 to the 8th power dyn/cm (pressure integrated through the ice thickness) is marginally able to ridge thick ice, according to the ridging model of Parmerter and Coon. These maximum values occur near Greenland, where Wittmann and Schule report intense ridging. When the wind stress is reduced to one third of the strength first assumed, realistic speeds and vorticities are obtained, and the maximum pressures are reduced to one third of the above value.

Sackinger, W.M., **Arctic coastal research on sea ice and offshore permafrost**, *Arctic Bulletin*, Vol. 2, No. 10, 1977, pp. 169-176, refs.

A review is presented of research programs conducted since 1973 by the Geophysical Institute of the University of Alaska and funded by the NOAA Sea Grant Program and the Alaska Oil and Gas Association (AOGA). Ice movement has been studied using an ultrasonic transponder on the seafloor and a transmitter and several receivers on the ice sheet. Ice motion and ice ridge formation were observed by radar. Drifting ice floes will assault offshore structures in the "shorefast zone" during annual breakup and occasionally in midwinter, and drifting ice ridge fragments with a thickness equal to the water depth are possible with drift speeds up to 8.3 km/hr. Naturally occurring stresses in the shorefast ice were monitored by stress transducers in the ice. Periodic stresses are caused by tidal fluctuations. In late spring 1973, compressive stresses near the surface were correlated with solar heating effects. Currents under the shore-

fast ice are small. The pack ice internal forces, generated by winds acting over large areas, cause ice motion at times when local conditions are relatively calm. Satellite imagery was used to delineate the shorefast ice. Pressure and ice motion forecasts can now be related. A temperature profile with depth of the offshore permafrost was obtained through drilling and coring projects. Seismic refraction methods mapped the permafrost. A subsea, ice-bonded permafrost vertical section was charted extending from shore into Prudhoe Bay for 3.4 km with a temperature of -1.8°C in the upper boundary.

Schwaegler, R.T., **Effect of changing the yield surface and the kinematic relationship in the AIDJEX sea ice model**, *AIDJEX Bulletin*, No. 29, University of Washington, Seattle, July 1975, pp. 135-150, refs.

A prescribed set of construed motions are used to test three versions of a zero-dimensional model of the pack ice: model 1 neglects the elastic strain in the plastic state and has a circular yield surface; model 2 also neglects the elastic strain in the plastic state, but has a teardrop yield surface; model 3 has a teardrop yield surface, but included the elastic strain in the plastic state. A comparison of models 1 and 2 indicates that the circular yield curve produces more extreme values of stress and strength than the teardrop curve when both are subjected to the same deformation history. These differences in stress and p.@. become largest during periods of uniaxial divergence; little or no difference is observed during periods of isotropic divergence or convergence. Changes in the ice thickness distribution can also significantly affect the response of each model. A comparison of models 2 and 3 indicates that the inclusion of elastic strain during plastic deformation produces a more damped solution than is given when they are neglected. For the options used in this study, very small (1 to 1-1/2%) changes in stress and strength are observed between models 2 and 3.

Schwerdtfeger, W., **Meteorological aspects of the drift of ice from the Weddell Sea toward the mid-latitude westerlies**, *Journal of Geophysical Research*, Vol. 84, No. 10, October 1979, pp. 6321-6328.

Persistent, moderate to strong southerly surface winds, so-called barrier winds, developed along the east side of the Antarctic Peninsula when the prevailing easterlies over the central and southern Weddell Sea carry cold, stable air masses toward the 1200- to 2000-m-high mountain barrier. Because of the lack of observations from the Weddell Sea itself, wind data for the topographically similar Ross Ice Shelf area are used to estimate the probable lateral extent of barrier winds. Frequency and duration of different types of winds at the key station Matinenzo (65°S, 60°W) indicate the importance of the barrier effect for the drift of large ice masses northward and northeastward to the relatively low latitude of 63°S. Such a guided discharge of ice into the belt of the subpolar and mid-latitude westerlies, not to be found in other sectors of the Antarctic, has a profound effect on the temperature conditions over the southern south Atlantic. Evidence for each of these statements is presented.

Seliakov, N.I., **Some observation on processes connected with the formation of ice**, TT-60 13694, 1951, 4 pp., Translation from Akademiia nauk SSR, *Dokaldy*, Vol. 70, p. 821-824, 1950.

Ice crystals are made visible for study purposes by 3 methods: (1) dessication, (2) etching or outlining, and (3) light projection. It was determined by these methods that ice crystals were a few cm. in size. The orientation of ice crystals in relation to the freezing water surface and the physical properties of melting ice were determined by developing the melting pattern method, a technique first devised by Tyndal. Two methods of freezing water are described: (1) side cooling and (2) surface cooling with constant pressure underneath the ice. Two types of "freezing out" (vymorazhivanie) are distinguished: (1) when evaporation takes place during the crystallization process, and (2) when evaporation originates from the solid phase surface, after the liquid has been totally crystallized. The latter process is called sublimation.

Semtner, A.J., Jr., **On the development of a seasonal change sea-ice model**, *Journal of Physical Oceanography*, Vol. 6, No. 5, September 1976, pp. 679-685.

A three-dimensional thermodynamical model of sea ice has been developed that is capable of simulating seasonal changes over the Arctic and Antarctic regions. The model is patterned after the earlier work of Maykut and Untersteiner (1971) and Semtner (1976). Instead of specifying the fluxes of energy at the top of the ice, as is usually done in sea ice modeling, the components of surface energy balance are computed from observed climatological atmospheric data. Also, a new parameterization of leads by Semtner (1976) is tested and shown to improve the simulation. The model results agree with observations in the Arctic, but they are less successful in the Antarctic. Possible reasons for deficiencies of the model are that ice transport is not included and oceanic heat flux is not properly accounted for. These aspects will be added and improved in future development of the model.

Semtner, A.J., Jr., **Model for the thermodynamic growth of sea ice in numerical investigations of climate**, *Journal of Physical Oceanography*, Vol. 6, No. 3, Boston, Massachusetts, May 1976, pp. 379-389, refs.

A model is presented whereby the thickness and

extent of sea ice may be predicted in climate simulations. A basic one-dimensional diffusion process is taken to act in the ice, with modification resulting from penetration of solar radiation, melting of internal brine pockets, and accumulation of an insulating snow cover. This formulation is similar to that of a previous study by Maykut and Untersteiner, but their introduction of a streamlined numerical method makes the model more suitable for use at each grid point of a coupled atmosphere-ocean model. In spite of its simplicity, the ice model accurately reproduces the results of Maykut and Untersteiner for a wide variety of environmental conditions. In 25 paired experiments, annual average equilibrium thicknesses of ice agree within 24 cm for 75% of the cases; and the average absolute error for all cases is 22 cm. The new model has fewer computational requirements than one layer of ocean in the polar regions, and that it can be further simplified if additional savings of computer time are desired.

Short, A.D., and Wiseman, W.J., Jr., **Coastal breakup in the Alaskan Arctic**, *Geological Society of America Bulletin*, Vol. 86, February 1975, pp. 199-202.

During observations of breakup along the Alaskan Arctic Coast, river flooding of the frozen nearshore zone, sea ice breakup, and beach thaw were examined. Spring river flooding, generated by earlier and inland melt, accompanies arrival of temperatures above 0°C on the coast. The extent of flooding over the nearshore ice is related to total flood discharge and coastal morphology. Along wave-controlled barrier-island coasts, flooding and bed load are confined to lagoons, whereas on fluvial-dominated coasts, floodwater and sediment spread across lobate delta fronts and offshore shoals. During this time marine influence is minimal as a result of protection afforded by sea ice cover. Sea ice melt continues through summer, and the final coastal sea ice breakup and ice dispersion depend on offshore Ekman transport, breakup of the offshore pack ice, and local bathymetry. The coastal ice breaks up 4 to 8 weeks after initiation of melt. Melt of ice and snow within the beach generates beach collapse and resultant unique arctic beach features, whereas flow of tundra snow melt across the beach produces micro-fans and micro-deltas.

Sobczak, L.W., **Ice movements in the Beaufort Sea, 1973-1975: determination by ERTS imagery**, *Journal of Geophysical Research*, Vol. 82, No. 9, Washington, D.C., 20 March 1977, pp. 1413-1418.

Remote sensing (ERTS) imagery was used to map the distribution of leads in the sea ice over the Beaufort Sea during late Feb. through early April in 1973, 1974, and 1975. A comparison of the bearings and speeds of ice movements obtained from ERTS-based maps with those of geostrophic winds calculated from average daily and weekly atmospheric pressure charts indicates that the ice drifts at about 1/100 of the speed of the geostrophic winds in a direction about 20 deg to the left of them. During early March 1973, before excessive ice breakup, the sea ice moved slowly, about 0.3 km/day, but during periods of rapid ice fracturing (March and April 1975), the sea ice moved at rates as high as 18.2 km/day.

Sodhi, D.S., **Ice arching and the drift of pack ice through restricted channels**, NTIS #ADA-044 218, August 1977, 11 pp., 23 refs.

Models originally developed to describe the arching and the movement of granular materials through hoppers or chutes are applied to the arching and drift of pack ice in straits and gulfs having lengths of 50 to 500 km. Verification of the usefulness of the models is attempted by making comparisons with ice deformation patterns as observed via satellite imagery in the Bering Strait region and in Amundsen Gulf. The results are encouraging in that there is a good correspondence between observed arching and lead patterns and those predicted by theory. In addition, values determined via the model for the angle of internal friction (approx 30 deg to 35 deg) and the cohesive strength per unit thickness (approx 2,000 N/m) are similar to values obtained by other approaches. It is estimated that if the wind velocity parallel to the Bering Strait exceeds approx 6 m/s, there will be ice flow through the strait.

Solomon, H., **A one-dimensional collision model for the drift of compact pack ice**, *Geophysical Fluid Dynamics*, Vol. 5, No. 1, May 1973, pp. 1-22, 16 refs.

Equations of motion governing one special case of the drift of compact ice are derived from direct consideration of the small-scale interactions between ice floes. It is shown that the limited horizontal compressibility of the ice pack can be incorporated into a 'fluid like' (non-rigid) continuum model. The 'compactness' (fraction of the naviface covered by ice) and an empirical 'interaction cross-section' of the ice floes are important parameters of the continuum model. The one-dimensional model derived here cannot be compared directly with data but fills an important gap in existing theories between the continuum totally lacking in stiffness, on the one hand, and the solid ice sheet on the other.

Sverdrup, H.U., **Ice drift in the Weddell Sea**, NTIS #ADA-035 991, January 1977, 13 pp., 7 refs., Translation of *Annalen der Hydrographie und Maritime Meteorologie*, Vol. 65, No. 9, 1928, pp. 265-274.

Factors determining ice drift in the Weddell Sea are analyzed mathematically on the basis of observations made along Siberia and modified to fit local hydrographic conditions. Data are tabulated and graphed on the relation between ice drift and wind with constant wind conditions and increasing ice resistance, surface-

drift velocity and friction depth assuming ice resistance to be proportional to the square of the surface velocity, seasonal variations in the wind factor and deviation angle, seasonal variations in the coefficients of ice resistance and wind action, and the relation between wind and ice drift under quasi-stationary conditions. Ice drift in the Weddell Sea is determined by wind action on the ice, the resistance of ice against ice, the depth of the friction layer in the water, and the deflecting force of the earth's rotation. The importance of the wind factor in the Weddell Sea is greater than in the open Arctic Ocean since the ice offers a greater surface to the wind.

Treshnikov, A.F., *Problems of the Arctic and Antarctic*, Number 41, 1973, Office of Polar Programs, National Science Foundation, Washington, D.C, Special Foreign Currency Science Information Program, Report No. TT-75-52018, 138 pp., Translation of *Problemy Arktiki i Antarktiki* (USSR), Sbornik Statei, No. 42, 1974, by Y.V. Kathavate.

Partial contents: Geomorphology of the floor of the Norwegian and Greenland Seas; On the study of semimonthly tidal phenomena in the Arctic; Centers of atmospheric action and solar activity; Experiment in organizing oceanographic investigations of the ice-edge zone of the Chukchi Sea; Classification of Antarctic Sea ice by the conditions of its formation; a socio-psychological study of typical motives for joining the Soviet Antarctic Expedition; The method of calculating and analyzing some wind characteristics.

Untersteiner, N., **Calculating thermal regime and mass budget of sea ice**, *Symposium on the Arctic Heat Budget and Atmospheric Circulation*, 1966, pp. 205-213, University of Washington, Seattle, Department of Atmospheric Sciences, Report No. TR-27.

A mathematical model for predicting thickness and temperature of sea ice is described. It consists of the equations of heat conduction for both snow and ice, with variable thermal constants and a term representing internal heating by radiation. The boundary conditions at the interfaces with the atmosphere and the ocean are given in the form of heat budget equations. The fluxes of radiative, latent, and sensible heat are treated as independent parameters (except for the infrared emission from the surface, which is calculated). This model is being programmed for long-term (several years) integration with various combinations of heat fluxes in the atmospheric and oceanic relation of climatic change to ice productivity.

Untersteiner, N., **Calculations of temperature regime and heat budget of sea ice in the central Arctic**, *Journal of Geophysical Research*, Vol. 69, No. 22, 15 November 1964, pp. 4755-4766, University of Washington, Seattle, Report No. TR-10.

The equation of heat conduction, including variable thermal conductivity and specific heat, and internal heat source diminishing with depth, and an advective term, is integrated numerically for sea ice of equilibrium thickness. The annual cycle of thickness (ablation-accretion) is imposed as an external parameter. The boundary values for temperature and the vertical distribution of the salinity are taken from empirical data. The computed temperature field is in good agreement with observations. The thermal history of individual particles of ice, the relative effect of the internal heat source (penetrating solar radiation), heat storage, and the annual cycle of heat flux by conduction at various depths are described. The observed maximum of brine volume at 40- to 70-cm depth is explained as the combined effect of salinity profile and internal absorption of radiation. The requirement that heat flux in the ice plus the heat equivalent of surface ablation equal the heat flux in the atmospheric boundary layer is well met by Badgley's values of radiative and turbulent heat transfer. During the melting season, June 15 to August 20, the surface of the ice receives about 4.5 kcal/cm2 and loses, during the freezing season, August 21 to June 14, an only slightly greater amount of heat to the atmosphere.

Wittman, W., *The Naval Oceanographic Office of Research Support Program in Sea Ice Prediction*, U.S. Navy, Sea Ice Branch, Washington, D.C, See Citation No. 72-2B-0573, 1969, pp. 6-8.

Efforts of the Naval Oceanographic Office to improve ice predictions for surface ships and submarines in pack ice covered waters are described. These efforts can be divided into two parts. First, attempts have been made to formulate crude empirical relationships that express polar ice behavior as a function of known and/or predictable meteorological and other environmental factors. Insufficient understanding of dynamical ice processes limit this approach. Second, efforts have been made to improve sea ice observational techniques; experimentation with remote sensor equipment utilizing aircraft platforms and drift stations has been considerable. Future plans of the program are described.

Zhmurko, V.A., **Radar observations of the drift of marked ice floes**, *Oceanology (USA)*, Vol. 11, No. 6, 1971, pp. 919-23.

Some aspects of ice drift observations by radar, are described from the author's experience in Tatar Strait from 1963-1964 to 1966-1967. Shore and ship-based radar and passive ice-mounted reflectors with different reflecting surfaces, installed at the vertices of a right triangle, were used. This made it possible to compute hummock formation and breakup from divergence. The divergence values were reduced to an ice concentration 10 tenths and to the latitude of Cape Krasnyy Partizan. The harmonic constants of Hummock formation and breakup due to tides were computed and divergence values were determined for

variable winds. Investigations of hummocking and breakup are important not only for navigation through ice, but also because they showed that under ice currents have a strong effect on ice dynamics in Tatar Strait, which is commensurate with that of the wind. Ice divergence lags 3.3 hours behind the velocity maxima of underice total currents. This is close to the 3 hours determined by Zubov for Arctic Seas.

## D. River Ice

Ackley, S.F., Hibler, W.D., III, Kovacs, A., and Weeks, W.F., **Top and bottom roughness of a multi-year ice floe**, *Symposium on Ice and Its Action on Hydraulic Structures (2nd)*, Leningrad, 26-29 September 1972, pp. 130-142, 4 refs.

A spectral study of the snow and ice topography on a multi-year ice floe has shown that the snow cover, although attenuating the roughness amplitude of the ice surface, does not cover it completely. In general the snow surface variance is lower by a factor of 1/3 to 1/4 as compared to the ice surface variance. The correlation between snow and ice surface roughness is highly significant for long wavelengths (greater than 8 m), but fails to be significant for short wavelengths (less than 4 m). The results agree with what might be expected intuitively in that long wavelength variations are not masked appreciably while short wavelength variations are well hidden. Although the ice sheet as a whole is in free-floating, isostatic equilibrium, pronounced local deviations from isostatic equilibrium are common. The trend is for ice drafts to deviate more than expected from isostacy for thin ice and less than expected for thick ice. Estimates are also made of the number of ice thickness measurements required to obtain the mean thickness of the multi-year floe to any specified accuracy.

Ashton, G.D. and Calkins, D.J., **Arching of model ice floes: effect of mixture variation on two block sizes**, NTIS #ADA-033 841, November 1976, 11 pp., 5 refs.

A study of arching of mixed, square fragmented ice floes at an opening in an ice boom is documented, using results from a model study in which two sizes of plastic blocks represented real ice. A power function, relating the upstream ice concentration to the ratio of a characteristic block dimension to the gap opening, is found adequate to distinguish between arching and nonarching events for block mixtures of two component sizes. It is demonstrated that when the respective total areas of the two block components are nearly equal, a minimum ice concentration initiates an arch across the opening. As the mixture of two sizes of blocks approaches a uniform (one-sized) mixture, a higher concentration of ice is needed to initiate the arch. When the ratio of the block dimension to the gap opening is equal to or less than 0.10, arching of the fragmented ice is not possible, even when the upstream ice discharge exceeds the maximum discharge of ice through a gap opening. The distribution of fragmented ice areas is an important parameter in establishing the minimum size of opening at which an ice boom will retain its arching capability.

Ashton, G.D., **Field implications of the formation of ice ripples**, *Symposium on Ice and Its Action on Hydraulic Structures (2nd)*, Leningrad, 26-29 September 1972, pp. 123-129.

The results of a recent experimental and analytical study are used to predict the conditions under which ice ripples form on the underside of river ice curves. A relationship between the wavelength of the ripples and the flow velocity is proposed and compared with existing field data. The effect of flow depths on the wavelength-velocity relationship is examined and found to be small.

Berdennikov, V.P., Buzin, V.A., Chizhov, A.N., Donchenko, R.V., Filippov, A.M., Kozitskii, E., Molchanov, A.K., and Vlasov, V.P., *Investigation and Calculations of Ice Jams*, NTIS #ADA-014 887, March 1975, 106 pp., Numerous refs., For Russian original see CRREL #29-1193 through 29-1198.

The collection is concerned with the questions of ice jam phenomena on rivers. The articles indicate the quantitative tendencies in the formation of ice jams on the Dnestr River based on materials obtained from observations of past years, full-scale and model investigations, the results from studying the tendencies in ice jam phenomena in the tailwaters of the HES, plus a procedure for calculating these occurrences. The authors also expound on the experience gained in modeling the movement of slush ice beneath an ice cover and the results obtained from aerial photographing of jams occurring on rivers. The compendium is intended for hydrologists and hydraulic engineers.

Burdick, J., Esch, D., Johnson, P., McFadden, T., Osterkamp, T., and Zarling, J., **Yukon River breakup 1976**, *International Symposium on Cold Regions Engineering (2nd)*, Fairbanks, Alaska, 12-14 August 1976, Proceedings, University of Alaska, Cold Regions Engineers Professional Association, 1977, pp. 592-596, 8 refs.

A recently completed bridge across the Yukon River, north of Fairbanks, Alaska, provides an opportunity for studying breakup processes and measuring ice forces on a structure in a major river where ice conditions are near the continental extreme. Above the bridge the river flows through the 200-mile long Yukon Flats, a marshy, lake-dotted area. The multiple channels of the river meander back and forth providing a very large water surface for winter ice production. The winters are long and severely cold with only light snowfall so the Flats produce very large quantities of thick ice that pass through the bridge each spring. The bridge is a six-span continuous orthotropic-deck structure spanning a 2,000-foot channel. Five reinforced concrete piers secured to bedrock with prestressed rock anchors are subject to river ice. Steel legs rise from the tops of the piers to carry the deck. USACRREL, University of Alaska, and Alaska Department of Highways personnel observed ice-bridge interactions during the 1976 breakup. Time

lapse and regular speed Super 8 movie and 35mm still photographs were taken. Several types of ice failure were observed including crushing along the full width of the piers, splitting, combined splitting and crushing, and non failure.

Calkins, D.J., Hutton, M.S., and Marlar, T.L., **Analysis of potential ice jam sites on the Connecticut River at Windsor, Vermont**, NTIS #ADA-031 572, September 1976, 31 pp., 11 refs.

Sections in the Connecticut River where ice jam potential is high were identified through the use of low altitude black and white photographs taken during low-flow, ice-free conditions. The hydraulics and mechanics of ice jam initiation were investigated in the river reach where these sections were identified. Certain areas were found in the river that had a high susceptibility to ice clogging, but this high potential decreased with increasing discharge because of the improved surface conveyance of the ice through the reach. The stability of ice floes was established along the channel, but the floes generally became unstable as the flow increased. This was calculated by using a Froude number criterion. Grounding locations for ice became evident when the critical Froude number was zero for a given thickness and water depth. No single factor was determined to be responsible for initiating the ice jams in the Connecticut River at Windsor. Apparently there existed a multitude of interacting conditions: surface constrictions, possible high backwater conditions from the Brattleboro Dam, a solid ice cover in the transport from the Windsor area, deep pools followed by shallow depth sections upstream of bridge piers, a greater ice thickness accumulation of fragmented floes than would result if a uniform cover could be established in the same reach, and the diurnal fluctuation of river stage caused by the release of water at Wilder Dam.

Calkins, D.J., **Physical measurements of river ice jams**. *Water Resources Research*, Vol. 14, No. 4, August 1978, pp. 693-695, 5 refs.

River ice jam measurements have always been relatively difficult to obtain because of the uncertain stability of the floating ice mass. But recently two ice jams resolidified for about 3 weeks, allowing the ice thickness to be measured at several cross sections along their longitudinal profiles. The size distribution of surface ice floes in one of the jams was also evaluated from low-level aerial photography. The ice jams were found to be thickest at the downstream end, of the order of 4-5 times the thickness of the ice cover before breakup, and decreased almost linearly in thickness upstream. The largest surface ice floes measured in one ice jam ranged from 0.27 to 0.05 of the river's average width (45m). The largest floes were at the downstream end, and floe size decreased progressively with distance upstream.

Collins, C.M. and McFadden, T., **Ice breakup on the Chena River 1975 and 1976**, NTIS #ADA-043 070, June 1977, 44 pp., refs.

The breakup of the Chena River was observed and documented during the spring of 1975 and 1976. This study attempted to determine the potential for damage to the proposed Chena River flood control dam from ice and debris during breakup. Results of this study were compared to those of a 1974 companion study. In 1975, ice thicknesses were determined to be 15% thinner than in 1974 and ice volume was 33% smaller. No major ice floes were observed in 1975 and no significant flooding occurred, although the approaches to a bridge at the damsite were eroded by debris and high water immediately after breakup. The 1976 breakup was milder than that of 1975. Minor flooding in the lower river was caused by jamming of a few large ice pieces, but no property damage resulted.

Devik, O., **Thermal and dynamic conditions of ice in streams, as applied to Norway**, NTIS #ADA-027 019, March 1976, 119 pp., 53 refs.

This paper gives the results of early studies (1926-1928) on the physical problems of ice formation and applies the analysis to practical examples, primarily to Norwegian conditions.

Donchenko, R.V., **Conditions for ice jam formation in tailwaters**, NTIS #ADA-052 396, March 1978, 17 pp., 11 refs., For Russian original see CRREL #30-3447.

On the basis of studies on the dynamics of the ice cover edge the following peculiarities were found in the formation of jams in tailwaters. Formation of ice jams in tailwaters is a consequence of the dynamic destruction and separation of the edge with increased discharges. The process of dynamic destruction of the edge evolves by the formation of cracks along the shore, debacles, and hummocking on the section within which during discharges the size of fluctuation in the water level is 3-4 times greater than the thickness of ice on the edge during its formation. Jams are formed at the jointing of the intact ice cover and the shattered field under the influence of the forces of the flow and pressure of the ice field that exceeds the resistance of the ice. The amount of the greatest jam level is in direct dependence on the amount of maximum water consumption in the period of jam formation. An increase in discharges during the formation of ice jams promotes the increase in capacity of the jam, and as a consequence a reduction in the winter coefficients occurs. Regulation of the GES routine depending on the conditions for ice cover edge formation on the section within the diurnal lag time is a necessary condition for the movement of the edge in the tailwater without jam formation.

Johnson, P.L. and Kistner, F.B., **Breakup of ice, Meade River, Alaska**, NTIS #AD-667 946, October 1967, 12 pp., 12 refs.

The climatic conditions and chronology of ice breakup of the Meade River, Alaska, in 1966 are reported and documented photographically. These observations and the interpretation of aerial photography suggest that ice damming, flooding, and dam release are the typical patterns of breakup that progress repetitiously downstream. The implications of ice breakup on plant succession on river bars and on channel erosion are discussed.

Kane, D.L. and Slaughter, C.W., **Seasonal regime and hydrological significance of stream icings in central Alaska**, *The Role of Snow and Ice in Hydrology; Proceedings of the Banff Symposia*, Vol. 1, September 1972, Geneva, Switzerland, WMO-IAHS, Unesco, 1973, pp. 528-540, 16 refs., Includes a French summary.

Many streams in Arctic and sub-Arctic regions are characterized by accumulations of ice in the channel and nearby flood plain during winter months. Field data on the rates of growth of this icing and on various climatic factors has been collected at a small research watershed near Fairbanks, Alaska. The volume of icing growths is estimated from aerial photographs. Hydrologic implications are derived by comparing the volume of these icings with other elements of the hydrologic cycle. Discussion on how the hydrologic cycle is modified by these ice accumulations is also included.

Korzhavin, K.N., **Action of ice on engineering structures**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, 1971, 321 pp., Draft translation of mono. **Vozdeistvie Lda na Inzhernernye Sooruzheniya**, 1962, 202 pp.

Contents: Nature of interaction of ice structures; Survey of physico-mechanical properties of river ice; Pressure of ice on structural abutments (supports); other cases; Natural methods of determining ice pressure on structural supports; Experience gained in determining actual pressure of ice on structures by use of kinematic method; Passage of ice and size of ice-admitting openings; Findings and conclusions.

Latyshenkov, A.M., **Design factors for river ice booms analyzed**, NTIS #ADA-014 886, September 1975, 13 pp., Translation of *Gidrotekhnicheskoe stroitel'stvo*, Vol. 15, No. 4, 1946, pp. 13-19.

Model studies were made to determine hydraulic characteristics of structures for protecting ships wintering in rivers under conditions similar to those observed in European and Siberian rivers (ice-cover thickness up to 1.8 m and river depth to 12 m). The experiments are described in detail, and data are mathematically analyzed. Formulas and graphs for calculating the stresses as a function of ice-cover thickness, flow speed, and width and depth of the river are suggested. The ice pressure on protective booms in a stream wider than 30 m was found to increase 85-90% due to the friction between the lower ice surface and flowing water. The friction coefficient is proportional to the ratio of ice thickness to flow depth.

**Model investigations of ice entrainment beneath edge of an ice cover**, NTIS #ADA-009 694, May 1975, 8 pp., 4 refs.

River flow model investigations of the drawing in of slush and ice under the edge of an ice sheet are a component part of the study of ice-dam and ice-jam formation processes in rivers, as well as a stage in the experimental development of methods of the hydraulic regulation of slush and ice movements. By using this type of research, it is possible to determine the conditions governing the drifting of ice blocks of various lengths, widths, and thicknesses under an ice sheet for flows having different hydraulic parameters.

Samide, H.R. and Slaughter, C.W., **Spring breakup of the Delta River, Alaska**, NTIS #AD-724 683, April 1971, 33 pp., 12 refs.

Spring "breakup" of snow and ice on the Delta River, Alaska, was monitored in 1967. Breakup on this braided river was a relatively calm event, with gradual development of open-water channels from headwaters to mouth. Air temperature data at Big Delta, near the mouth of the river, indicated an accumulation of 30 positive degree-days (F) above 32°F, using mean daily values, prior to first observation of continuous open water from headwaters to mouth; a corresponding value, but using maximum daily air temperatures, was 224 degree-days (F). A photographic sequence of breakup at several points along the river is included.

## E. Forecasting

Ashim, L.D., **The operational determination of wind stress on the Arctic ice pack**, Master's Thesis, Naval Postgraduate School, Monterey, California, #251450, September 1977, 78 pp.

The performance of routine FNWC sea level pressure analyses and forecasts in the Beaufort Sea is evaluated for driving an ice model. The geostrophic winds determined from the FNWC pressure fields are compared to geostrophic winds determined from the AIDJEX experiment observations. A simulation with the AIDJEX model has been run using VNWX sea level pressure analysis fields for the period 15 to 25 May 1975 and compared to the AIDJEX results. RMS sea level pressure errors of about 3 mb were found with analysis errors reduced by about 1 mb when one AIDJEX observation was included in the analysis. Geostrophic winds had speed differences of about 40% and direction differences of about 50 deg. The FNWC simulation with the AIDJEX model produced a position error of about 7 km for one station over the ten day run. Recommendations are made to improve the FNWC hemispheric fields in the Arctic for application to ice forecasting.

Barnett, D.G., **Long range ice forecasting for Alaska's north coast**, *Sea Technology*, Vol. 17, No. 7, July 1976, pp. 24-27, Fleet Weather Facility, Suitland, MD.

Preliminary attempts to develop the capability of providing accurate longer-range forecasts have resulted in the discovery of strong relationships between summer ice conditions along the North Slope and meteorological conditions in the preceding April. Aprils preceding favorable summers were typified by a relatively weak Siberian high and a strong high pressure system over the Arctic Basin, whereas Aprils preceding unfavorable summers were typified by a strong Siberian high and a displaced and generally weaker Arctic high. If the relationship is valid, a quantitative measure of the April strength and position of these pressure systems should produce a valuable long-range forecast aid. A table is provided giving selected sea ice data and the severity index for the north coast of Alaska, 1953-1975.

Beylinson, M.M., **Experiment in making long-range ice forecasting in southern Kazakhstan**, Nauchno-Issledovatel'skiy Institut, *Trudy*, No. 41, 1971, pp. 124-128.

Long-range forecasts for the start of fall ice flow and the beginning of freeze-up on the water bodies of Kazakhstan are based upon the meridional index of the atmospheric circulation and inverse associations between the meterological elements of the warm and cold periods. Also, the characteristics of the formation time for the westerly ridge of the Siberian anticyclone over Kazakhstan are used. The authors analyze 44 long-range forecasts of the beginning of ice freeze-up on Lake Balkhash, made during 1960-1969, according to the method developed by the Kazakhstan Scientific Hydrometeorological Institute. An analysis of unverified forecasts (9 out of 44) shows that the method forecasts, a long time in advance (46-75 days), the inflow of cold air masses that do not always cause the freezing of a body of water. It is proposed that the forecasting of the onset of ice freeze-up should take into account the stage of cooling of the body of water at the moment the forecast is issued, by using the resulting thermal balance. The formulas for predicting the meridional inflow of cold air masses from northern latitudes and for predicting the beginning of freeze-up are presented.

Bilello, M.A. and Langway, C.C., Jr., **Prevailing wind directions in the Arctic Ocean**, *American Geophysical Union, Transactions*, Vol. 53, No. 11, November 1972, pp. 1014.

Prevailing monthly and seasonal surface wind directions were obtained from 1) weather records for 21 coastal stations around the Arctic Ocean and 2) a series of U.S. Navy wind charts for 15 to 20 locations in the arctic marginal seas and the ocean's interior. This information was combined and analyzed to develop 2 charts that depict the surface flow of air in these areas during the mid-summer and mid-winter months. Since the ice flow stations used in the offshore wind analysis are not permanently located, the Arctic Ocean was selectively divided into 6 zones. Three of these zones separate polar regions north of 84°N latitude, and 3 other zones each separate the seas bordering the north coasts of Europe, Siberian Russia, and North America. Except for a few stations where wind directions are apparently controlled by local influences, the results showed the following mid-winter patterns: 1) a near anticlockwise flow within the circle north of 75°N, 2) winds from the north in and near the Chukchi and Bering Seas, 3) northeast winds along the Alaskan coast and northwest along the Canadian Archipelago Islands, and 4) southwest and southeast winds along the northern coast of Europe and Asia respectively. Although the wind directions during mid-summer become more variable, the study showed that the prevailing surface winds for most areas in this season are nearly opposite those observed in winter.

Burkhart, M.D. and Wittman, W., **Sea ice, Part 2, Ice distribution and forecasting services, North American arctic waters**, *Mariners Weather Log*, Vol. 17, No. 6, November 1973, pp. 343-355, Naval Oceanographic Office, Washington, D.C., Office of the Oceanographer of the Navy, Alexandria, Virginia, 1973, 14 pp.

This is the second of a three part report on sea ice. Part 1 included background, history, and the major features and physical properties of sea ice. This, the

second, is a discussion of sea ice distribution in North American waters, and forecast services. Information is given on the major North American ice regimes: Baffin Bay, Davis Strait, and Labrador Sea, the Hudson Bay, Hudson Strait, and the Canadian Archipelago; and on the Canadian and USA ice observing and forecasting services, the Danish and Icelandic ice reporting services, and iceberg distribution and reporting services.

Burkhart, M.D. and Wittman, W., **Sea ice, Part 3, Ice distribution and forecasting services, Eurasian waters**, *Mariners Weather Log*, Vol. 18, No. 4, July 1974, pp. 219-229, Naval Oceanographic Office, Washington, D.C., Office of the Oceanographer of the Navy, Alexandria, Virginia, July 1974, 12 pp.

Sea ice distribution and forecast services in Eurasian waters are discussed along with the need for international cooperation as a prerequisite to an increase in understanding of the Arctic Basin ice cover and its interrelationships with ocean and atmosphere.

Gerson, D.J., **A numerical ice forecasting system**, Naval Oceanographic Office, Washington, D.C., Report No. N00-RP-8, October 1975, 146 pp.

This forecasting system provides estimates of current ice thickness and forecasts of ice formation and thickness for 62 locations in the Arctic. It also provides forecasting aids such as selected sea surface temperatures, snow depths, mean daily air temperature trends, and degree-day accumulations. The observations are obtained on magnetic tape from the National Meteorological Center on a near-real-time basis. The forecast techniques are statistical processes based on local climatology. The system presently is producing outputs on a daily basis. It is expandable in design so that as new forecasting methods are developed they can be integrated into the program, since the data base consists of all the synoptic weather observations.

Gordienko, P.A., **Ice drift in the central part of the Arctic Ocean**, Naval Oceanographic Office, Washington, D.C., Report No. N00-Trans-71, 1960, 45 pp., Translation of *Problemy Severa* (USSR), No. 1, 1958, pp. 5-29, by M. Slessers.

Ice displacements in the Arctic Ocean are analyzed with respect to direction and speed in various sectors of the ocean, taking into consideration the essential components of ice drift, such as wind drift, current, their fluctuations and shifts, atmospheric conditions, and other factors. The analysis is based on observational data concerning the drift of the Soviet North Pole stations, notably NP-3, NP-4, and NP-5 in 1954-1955. In conclusion, the prospects and accuracy in forecasting the ice movements and conditions that affect navigation on the Northern Sea Route are evaluated.

Hutcheon, R.J., **Forecasting ice in Cook Inlet, Alaska**, National Weather Service, Anchorage, Alaska, Report No. NOAA-TM-AR-5, August 1972, 20 pp.

The unique character of Cook Inlet makes the forecasting, and even the study of ice conditions, highly complex. The usual computations of ice thickness using the accumulated frost degree days is complicated by the occurrence of a number of periods during the winter when the average daily temperatures rise above freezing. The tidal action in the inlet further complicates any study of ice conditions by creating huge piles of ice on the mud flats and occasionally lifting them free. In addition a number of rivers drain into the inlet, creating areas of mostly fresh water, as well as releasing large fresh water ice cakes during river breakup.

Irvine, K.M., **Melting influences on the computer forecast of wind drift and concentration of sea ice**, Master's Thesis, Naval Postgraduate School, Monterey, California, 1965, 54 pp.

A computer program to provide five-day forecasts of the wind drift and concentration of sea-ice has been developed; however, one of the problems not considered is the effect of melting. Melting influences concentration in two ways: it reduces the amount of ice directly, and changes in thickness and concentration change the wind drift. A model to describe how ice-melt decreases thickness and concentration is developed and programmed. The results are used to modify the input data in the wind drift forecast; forecasts are compared with those based on wind drift alone. The modification enhances the use of the program as a forecast tool with the addition of normally available data. (Distribution limitation now removed.)

Knodle, W.C., **A computer program for forecasting the wind drift of sea ice**, Master's Thesis, Naval Postgraduate School, Monterey, California, 1964, 2 pp.

The theory and equations for forecasting the wind drift of sea ice, as previously developed by several researchers, are being used in the forecasting of that component of sea ice drift. The existing equations are modified and programmed for use with a comptuer to produce a forecast of wind drift, thus permitting rapidly made forecasts over large areas. Applicability and limitations, ways of handling other factors, i.e. permanent currents and melting and freezing, and methods for general improvement of the programs are discussed. The programs developed are useful as research tools and as applied to forecasting. (Available copy will not permit full reproduction. Reproduction will be made if requested by users of DDC. Copy is available for public sale.)

Kovalev, Y.G. and Nikolayev, Y.V., **Application of**

**discriminant analysis of long-term forecasts of ice in Arctic seas**, Leningrad, Arkticheskiy i Antarkticheskiy Nauchno-Issledova tel'skiy Institut, *Trudy*, Vol. 320, 1976, pp. 4-26, refs.

The results of the development of a method of long-range prediction of ice conditions in Arctic seas (Kara, Laptev, East Siberian, and Chukchi) on the basis of discriminant analysis are presented. The possibility of using elementary discriminant analysis, based upon the construction of maps of differences of pressure between two groups of observations (years with elevated pressure (type B) and a year with reduced pressure (type A)), is demonstrated. The method of objective analysis, based upon the transformation of initial information, a previously developed form of analysis of patterns of total ice conditions in Arctic seas, was applied to particular regions. The computation program was conducted with the Ural-2 and Minsk-32 calculators. Both variants of discriminant analysis yield positive results. Physical-statistical models for predicting ice conditions with a lead time of 1-6 mo and a confidence of 80-100% were constructed from the adopted criteria for all Arctic seas.

Lamb, H.H., **Problems and practice in longer-range weather and climate forecasting**, *Weather Forecasting for Agriculture and Industry, A Symposium*, Taylor, James A. (ed.), Cranbury, N.J.: Associated University Presses, 1972, pp. 34-43.

The special approaches required for long-range weather forecasting are outlined briefly. They include 1) understanding the relationship between the thermal condition of the Earth's surface and large-scale circulation during the seasonal progression; 2) study of the effects of anomalies of sea temperature and sea ice upon the atmospheric circulation and weather; 3) study of the effect of anomalies in the extent and distribution of snow; 4) study of any identifiable effects of the various kinds of disturbances on the sun and their course of development over various time scales; 5) identification of the effects of volcanic (and other dust and pollution) veils; 6) identification of time scales and manner of operation of periodic trends of statistically established sequential tendencies; and 8) identification of analogous situations. The working procedure in preparing a long-range forecast is outlined.

MacDowell, G.P. and Wittman, W.I., **Manual of short-term sea ice forecasting**, Naval Oceanographic Office, Washington, D.C, Report No. 82, May 1964, 142 pp.

The intent of this manual is to describe in as great detail as possible the procedures and techniques hitherto developed in provision of short-term ice forecasts. The procedures are formulated for application; all ice features to be predicted are correlated with known or readily predictable environmental variables.

Morozova, T.P., **Fluctuation of the southern boundary of polar ice in the Laptev Sea**, Naval Oceanographic Office, Washington, D.C., Report No. N00-Trans-126, 1963, 11 pp., Translation of *Problemy Arktiki i Antarktiki* (USSR), No. 1, 1959, pp. 5-10, by M. Slessers.

The interyearly and intrayearly (seasonal) displacements of the southern boundary of polar ice are discussed in connection with climatic and weather conditions in the area. The interrelation between the ice and weather conditions is analyzed on the basis of observational data concerning the phenomena so as to establish an acceptable base for ice forecasting on the Great Northern Sea Route.

Naval Oceanographic Office, *Antarctic Ice Observing and Forecasting Program - 1965*, Annual Report No. 2, Washington, D.C., Report No. N00-SP-80(65), January 1967, 26 pp.

The ice program conducted by the Naval Oceanographic Office principally in support of DEEP FREEZE 66 Antarctic operations is presented in this report. Methods of data collection and dissemination, ice forecasting, and various allied ice projects are discussed. A summary of ice conditions in the Ross Sea and McMurdo Sound is given graphically for the period October through December 1965. Ice concentrations were near normal during the DEEP FREEZE 66 operation but were somewhat heavier than those experienced during DEEP FREEZE 65, especially during the first half of the season. Rapid disintegration of the ice during late November resulted in nearly ice free conditions in the Ross Sea by mid-December. McMurdo Sound remained congested until mid-January because of persistent northerly winds that prevented the ice from drifting northward into warmer waters.

Naval Oceanographic Office, *Antarctic Ice Observing and Forecasting Program -1966*, Annual Report No. 3, Washington, D.C., Report No. N00-SP-80(66), July 1967, 35 pp.

The ice program conducted by the Naval Oceanographic Office principally in support of DEEP FREEZE 67 Antarctic operations is presented in this report. Methods of data collection and dissemination, ice forecasting, and various allied ice projects are discussed. A summary of ice conditions in the Ross Sea and McMurdo Sound is given graphically for the period October 1966 through January 1967. Ice concentrations were lighter than those experienced during DEEP FREEZE 66 and approximated DEEP FREEZE 65 conditions. Rapid disintegration during late November and early December resulted in open water to ice-free conditions in major shipping lanes.

Naval Oceanographic Office (Perchal, R.J.), *Report of the Antarctic Ice Observing and Forecasting Program - 1967*, Special publication, Washington, D.C., Report No. N00-SP-80(67), January 1969, 41 pp.

The sea ice program conducted by the Oceanographic Office principally in support of DEEP FREEZE 68

Antarctic operations is presented in this report. Methods of data collection and dissemination, ice forecasting, and allied ice projects are discussed. A summary of ice conditions in the Ross Sea and McMurdo Sound is given graphically by 6-day periods from October 1967 to February 1968.

Naval Oceanographic Office (Potocsky, G.J.), *Report of the Antarctic Ice Observing and Forecasting Program - 1968*, Special publication, Washington, D.C., Report No. N00-SP-80(68), July 1969, 35 pp.

The sea ice program conducted by the Oceanographic Office principally in support of DEEP FREEZE 69 Antarctic operations is presented in this report. Methods of data collection and dissemination, ice forecasting, and allied ice projects are discussed. A summary of ice conditions in the Ross Sea and McMurdo Sound is given graphically by 6-day periods from October 1968 to January 1969. Ice concentrations in McMurdo Sound were heavier than those experienced during DEEP FREEZE 68 and were the severest experienced during the past 4 years. Concentrations in the Ross Sea were slightly heavier than those experienced during DEEP FREEZE 68; however, the outer pack edge was significantly located further south toward the Ross Sea.

Naval Oceanographic Office (Perchal, R.J.), *Report of the Antarctic Ice Observing and Forecasting Program - 1969*, Special publication, Washington, D.C., Report No. NOO-SP-80(69), October 1971, 123 pp.

The sea ice program conducted by the U.S. Naval Oceanographic Office principally in support of DEEP FREEZE 70 Antarctic operations is presented. Methods of data collection and dissemination, ice forecasting, ice advisories, and allied ice projects are discussed. Ice conditions observed by aerial reconnaissance in the Ross Sea and McMurdo Sound from November 1969 to February 1970 are summarized. Ice conditions interpreted from satellite data generally by 1- to 4-day periods are also presented.

Naval Oceanographic Office, *The Eastern Arctic Ice Seasonal Outlook*, Special publication, Washington, D.C., Report No. N00-SP-80(68), 1968, 8 pp.

The seasonal ice outlook presents a written and graphic description of the ice conditions expected during forthcoming operations of the Military Sea Transportation Service (MSTS) in the eastern Arctic. Prognostic monthly ice charts with envelopes showing the expected range of sea ice from mid-May through mid-August are presented. Forecast trends for ports of major interest in MSTS resupply operations are given. The new World Meteorological Organization (WMO) ice terminology and symbols are used throughout the Outlook.

Naval Oceanographic Office, *Eastern Arctic Ice Seasonal Outlook*, Special publication, Washington, D.C., Report No. N00-SP-60(70), 1970, 11 pp.

Forecast trends for five major eastern Arctic ports resupplied by the Military Sea Transportation Service (MSTS) are listed in table 1. The normal escorted and unescorted entry date for each port is shown with the predicted trend. In addition, a written and graphic description of expected ice conditions is presented for Baffin Bay, Davis Strait, and the Labrador and east Greenland coasts between mid-May and mid-August. Monthly prognostic ice charts for this period include envelopes showing the maximum and minimum pack edges for each month.

Naval Oceanographic Office, *Report of the Arctic Ice Observing and Forecasting Program - 1963*, Special publication, Washington, D.C., Report No. NOO-SP-70(68), October 1969, 108 pp.

A summary of NAVOCEANO and NAVWEASERV ice operations during 1968 is presented. Operational aspects of obtaining and disseminating ice information and the ice forecasting and observing program are discussed. Ice charts including Danish data by 6-day periods depict observed synoptic ice conditions throughout that year. Locations of oceanographic stations occupied in the polar and subpolar regions are included.

Naval Oceanographic Office, *Report of the Arctic Ice Observing and Forecasting Program - 1966*, Annual Report No. 15, Washington, D.C., Report No. NOO-SP-70(66), October 1968, 94 pp.

A summary of NAVOCEANO and Danish ice operations during 1966 is presented. Operational aspects of obtaining and disseminating ice information and the ice forecasting and observing program are discussed. Ice charts depict observed synoptic ice conditions throughout the year. Locations of oceanographic stations occupied in the polar and subpolar regions are included.

Naval Oceanographic Office, *Report of the Arctic Ice Observing and Forecasting Program - 1967*, Special publication, Washington, D.C., Report No. NOO-SP-70(67), October 1968, 82 pp.

A summary of NAVOCEANO ice operations during 1967 is presented. Operational aspects of obtaining and disseminating ice information and the ice forecasting and observing program are discussed. Ice charts depict observed synoptic ice conditions throughout the year. Locations of oceanographic stations occupied in the polar and subpolar regions are included.

Naval Oceanographic Office, *Report of the Arctic Ice Observing and Forecasting Program - 1969*, Special publication, Washington, D.C., Report No. NOO-SP-70(69), August 1970, 180 pp.

The report contains a summary of Naval Oceano-

graphic Office and Naval Weather Service Ice Operations during 1969. It describes operational aspects of obtaining and disseminating ice information and the ice forecasting and observing program. Ice charts provided covering 6-day periods include Danish and satellite data and depict observed synoptic ice conditions. Locations of oceanographic stations occupied in the polar and subpolar regions are included.

Naval Oceanographic Office, *Report of the Arctic Ice Observing and Forecasting Program - 1970*, Special publication, Washington, D.C, Report No. NOO-SP-70(70), January 1972, 250 pp.

The report contains a summary of Naval Oceanographic Office and Naval Weather Service ice operations during 1970. It describes operational aspects of obtaining and disseminating ice information and the ice forecasting and observing program. Ice charts including Danish data depict observed synoptic ice conditions throughout the year. Ice conditions interpreted from satellite photographs are included separately. Locations of oceanographic stations occupied in the polar and subpolar regions are included.

Naval Oceanographic Office (Mitchell, P.A.), *Report of the Arctic Ice Observing and Forecasting Program - 1971*, Annual Report No. 20, Washington, D.C., Report No. NOO-SP-70(71), May 1974, 224 pp.

This report of the ice program conducted during 1971 in the North American Arctic, the last of this series, was conducted by the Naval Oceanographic Office. Methods of collection and dissemination of ice data, ice forecasting, forecast verification, and interpretation of satellite ice observations are discussed. Sea ice distribution in the eastern arctic was generally normal or slightly heavier than normal. Expected dates for escorted and unescorted entry into 5 selected eastern Arctic ports were forecasted. Conditions for escorted entry at 3 of these ports occurred as predicted. Escorted entry at the 2 remaining ports occurred 1 to 9 days later than forecast. Conditions for unescorted entry also occurred as predicted at 3 of these ports. Unescorted entry was possible 6 days later than forecast at one port and 20 days earlier than forecast at the fifth port. Ice conditions in the western Arctic were heavier than normal for the third consecutive year, especially in the Bering Sea during spring. Ice conditions, based on aerial and satellite data in the eastern and western sectors of the Arctic and data observed over the Arctic Basin during 2 BIRDS EYE missions, are shown graphically.

Nikol'skaya, N.A. and Senyukov, V.L., **Long-term forecast of ice in the Danish Sound**, U.S.S.R. Gidrometeorologicheskiy Nauchno - Issle dovatel'skiy Tsentr SSR, Leningrad, *Trudy*, No. 164, 1976, pp. 78-85, refs.

The Danish Sound is a region of intense commercial fishing by many countries, including the U.S.S.R. For marine safety and productive fishing, it is necessary to understand and predict the ice conditions in this region. Regression equations are given for predicting seasonal (April-Aug.) ice in the Danish Sound in terms of percentage of ice cover. Correlations are calculated for ice conditions and several large-scale parameters, including the influence of the Icelandic depression.

Office of Polar Programs, National Science Foundation, Special Foreign Currency Science Information Program, **Ice forecasting techniques for the Arctic seas**, Washington, D.C., Report No. TT-75-52077, 1976, 236 pp., Translated from *Glavnoe Upravlenie Gidrometeorologicheskoi Sluzhby* (USSR), No. 292, 1970.

Contents: Method for calculating the distribution of ice thickness in the Arctic Seas during the winter period; methods of long-term hydrometeorological forecasts for the Arctic; Utilization of the numerical method of calculation for the prognosis of autumn-winter ice conditions in the Arctic seas; Peculiarities of ice formation in the Arctic seas; On the close relationship between the mean monthly air temperature of polar stations in the region of Franz Josef Land; On the importance of planetary force in the changes in the ice cover of the Arctic seas; On the importance of using characteristics of Atlantic waters as a forecasting factor; On the stability of ten-day temperatures in the Eastern Arctic; A method of calculation of ice conditions.

Olbruck, G., **Forecasting drift ice off northern Iceland**, *Der Seewart*, Vol. 33, No. 2, Hamburg, April 1972, pp. 59-63.

The method of forecasting ice for an entire year for Iceland, developed by Pall Bergthorsson, is described, and its application is illustrated. The method is based upon the hypothesis that the atmospheric temperature on Jan Mayen can be used to forecast ice for Iceland six months in advance, since drift ice at Jan Mayen, on the average, requires a half year to reach the waters of northern Iceland. The procedure employed to construct a forecasting formula is described, and a power formula expressing ice occurrence as a function of weighted Jan Mayen atmospheric temperatures for June-Nov. is presented. The correlation between predicted and actual occurrence of ice was 0.93-1.0. An example of a forecast is presented. This article is a summary of the paper by P. Bergthorsson in *Jokull*, Vol. 19, 1969, pp. 43-52.

Potocsky, G.J., *Alaskan area 15- and 30-day ice forecasting guide*, Naval Oceanographic Office, Washington, D.C., Report No. NOO-SP-263, February 1975, 197 pp.

Procedures are detailed for preparing 15- and 30-day forecasts of ice edge movement, ice growth, and ice disintegration at Alaskan and other coastal and

offshore sites using current ice and prognostic environmental data. A statistical method for forecasting ice edge movement and ice distribution changes is given in this guide since this method has proven most useful and has yielded the best results. Frost degree day, related ice growth, and estimated ice disintegration curves are included for 14 stations. Background data on environmental factors related to growth, drift, and disintegration of sea ice throughout the Alaskan area include 15-day mean, median, and extreme means covering the 17-year period from 1954 through 1970 for semimonthly periods.

Rogers, J.C., **Evaluation of techniques for long-range forecasting of air temperature and ice formation**, National Oceanic and Atmospheric Administration, Ann Arbor, Michigan, Report No. NOAA-TM-ERL-GLERL-8, January 1976, 29 pp.

Four techniques for making long-range air temperature forecasts were evaluated by using wintertime (November through February) data from around Lakes Superior, Huron, and Michigan. The purpose of the evaluation was to find a technique for forecasting air temperature that could be applied to ice forecasting on the lakes. The four techniques analyzed were: (1) The use of cycles and oscillations; (2) The extrapolation and kinematic process used by the National Meteorological Center, which results in forecasts in the Average Monthly Weather Outlook; (3) Conditional probabilities, and (4) A Markov chain equation.

Timokhov, L.A., **Dynamics and kinematics of ice floes**, University of Washington, Seattle, Division of Marine Resources, Report No. AIDJEX-70-3, 1 September 1970, Translation of Arkticheskii i Antarkticheskii Nauchno-Issledovatei-skii Institut, *Trudy* (USSR), Vol. 281, 1967, pp. 130-136, by J. Buechner.

Characteristics detail of both dynamics and kinetics of ice floe lead to specific models stated in equations. The shift of ice floes must be considered simultaneously with phenomena related to ice compactness. Ice floes are capable of increasing, as well as leveling, compactness. The question of whether the finite-difference formulation of the equation describing the behavior of the ice cover should be preferred relates to the question of whether there exist physical phenomena that require finite-difference calculus for their description--i.e., the possiblity of describing these phenomena no longer exists in the transition to the limit.

Tyutnev, Y.A., **Long-range prediction of the dates of ice appearance in the coastal regions of the Black and Azov Seas**, U.S.S.R., Gidrometerologicheskiy Nauchno-Issledovatel'skiy Tsentr SSR, Leningrad, *Trudy*, No. 83, 1971, pp. 84-86.

The possiblity of developing significantly reliable long-range associations for predicting the dates of ice occurrence in the Black and Azov Seas is investigated by taking the atmospheric circulation index in the first natural synoptic period as the principal index of the atmospheric temperature influence upon ice phenomena. In determining forecasting relationships, the fundamental argument taken was the geopotential field of 500-mb surface (H.SUB 5..SUB 0..SUB 0.) above the first natural synoptic region, expanded into series of Chebyshev polynomials. In addition, elementary fields were taken, which reflect the position and intensity of ridge and trough aloft, over the eastern region of the Atlantic Ocean and over the European U.S.S.R., respectively. They corresponded to the expansion coefficients. Another argument introduced was the mean atmospheric temperature of the third 10-day period of Oct. in Archangel; it characterized indirectly the direction of synoptic processes over the European U.S.S.R. Relationships were established by means of which the appearance of ice at several points in the Black and and Azov Seas could be predicted 1-1.15 mo beforehand.

Udin, I. and Ullerstig, A., **Numerical model for forecasting the ice motion in the Bay and Sea of Bothnia**, *Meteorologi och Klimatologi*, MMk No. 6, Norrkopping, Sweden, 1977, 40 pp., refs.

A set of equations has been derived to describe the drift and redistribution of sea ice on the mesoscale. A steady-state momentum equation with a balance of wind stress, water stress, Coriolis force, and internal friction has been combined with a mass equation, split into one equation describing changes in ice concentration. The ice is supposed to behave in a visco-plastic manner. A numerical ice forecasting model has been developed, based on these equations. It has been applied to a one-dimensional channel, a two-dimensional idealized basin, and to the Bay and Sea of Bothnia. Verifications have been made in three real ice situations. The results are encouraging, showing that even the relatively simple model can give shipping some information on the ice situation some days in advance. The model has been used in a basic version, and further developments are planned and sketched in the report.

Volkova, N.A., **Investigation of the ice conditions in the Arctic seas and methods of forecasting and computation**, University of Washington, Seattle, Division of Marine Resources, Report No. AIDJEX-72-16, October 1972, 138 pp., Translated from Arkticheskii i Antarkticheskii Nauchno-Issledovat-elskii Institut, *Trudy* (USSR), Vol. 303, 1971.

The document is a Russian-to-English translation (for the National Science Foundation by the Israel Program for Scientific Translations) of the first 11 papers printed in *Trudy* (Proceedings) of the Arctic and Antarctic Research Institute, Vol. 303. The papers cover a wide range of topics related to ice

conditions in the Arctic seas, including numerical modeling and forecasting.

Walsh, J.E., **Ice forecasting limitations imposed by the accuracy of atmospheric prediction models,** *AIDJEX Bulletin*, No. 36, May 1977, pp. 1-13, refs.

Forecasts produced by the operational prediction model of the National Meteorological Center are examined for errors that may limit the accuracy of sea ice model predictions. Errors in the predicted low-level height gradients and geostrophic winds are found to be no worse in the Arctic than in most mid-latitude land areas. However, the forecast skill approaches zero by 72 hr when the errors in the predicted geostrophic winds typically become as large as the geostrophic winds themselves. It is concluded that the application of the AIDJEX model to sea ice forecasting will be limited much more severely by the accuracy of atmospheric pressure forecasts than by the formulation of the ice dynamics.

Wilson, E.E., *Mariners Weather Log,* Vol. 17, No. 6, November 1973, 75 pp.

In addition to its regular sections, this issue contains the following articles: **Sea ice, Part 2 Ice distribution and forecast services, North American Arctic waters**; and **Ocean currents and coastal climates.**

# 3. Remote Sensing

## A. Satellite

Ackley, S.F. and Hibler, W.D., III, **Measurement of Arctic Ocean ice deformation and fracture patterns from satellite imagery**, *AIDJEX Bulletin*, No. 26, September 1974, pp. 33-47, 12 refs.

Imagery of sea ice was analyzed to (1) measure ice deformation by remote sensing techniques and (2) estimate correlation of the deformation with atmospheric driving forces so that the primary winter contribution to the atmosphere-ocean exchange can be calculated. The distribution of ice openings from VHRR infrared images obtained in March 1973 by the NOAA-2 satellite over the Beaufort Sea was compared with the changes in the atmospheric pressure field during this period. Measured divergence rates were an order of magnitude higher than previously seen in this area. The general divergence of the pack correlated with the presence of a prolonged high pressure system in the region. It could significantly change the ice mass balance of a large region for a given year by increasing the amount of thin ice available that is subsequently piled up in pressure ridges.

Ackley, S.F., Anderson, D.M., Crowder, W.K., Hibler, W.D., III, and McKim, H.L., **Mesoscale deformation of sea ice from satellite imagery**, *Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources*, NTIS #AD-787 130, 1974, pp. 563-573, 10 refs.

Sequential mesoscale movement and deformation in the pack ice approximately 90 km northeast of Point Barrow, Alaska, have been observed in the ERTS-1 multispectral imagery of 19 to 22 March 1973. At this latitude, sidelap of adjacent ground tracks of daily overpasses is about 75%. This sidelap, together with the coincidence of five cloud-free days and major westward movement of the pack in the Beaufort Sea Gyre, permitted observation of drift and deformation in an area of about 14,000 sq km. Strain calculations using several 10-point arrays yielded shear and divergence rates as large as 0.5% per hour. Continuous deformation measurements through the fast ice/pack ice boundary indicated a sharp change in the sign of the vorticity as the shear zone was crossed. Measured drift velocities varied from 0.24 m/sec to 0.4 m/sec (0.9 to 1.4 km/hr). These results indicate that detailed deformation and movement data can be obtained from sequential ERTS-1 images. Such data are useful for determining scaling effects in the ice velocity field and for testing existing mathematical models of the response of sea ice to meteorological and hydrodynamic stresses.

Alishouse, J.C., Baker, D.R., McClain, E.P., and Yates, H.W., **Potential of satellite microwave sensing for hydrology and oceanography measurements**, National Environmental Satellite Service, Washington, D.C., Report No. NOAA-TM-NESS-26, March 1971, 22 pp.

Microwave radiometers on unmanned satellites appear usable for detecting sea-ice boundaries through clouds and for obtaining information of sea-surface roughness and temperatures. With the increasing tempo of theoretical and experimental studies in microwave sensors and antenna technology, there appears to be considerable potential for microwave measurements from earth satellites applicable to NOAA's hydrologic and oceanographic services.

American Society of International Law, **A global satellite observation system for earth resources: problems and prospects**, National Science Foundation, Washington, D.C., 1975, 183 pp.

This report explores the possibilities of actively applying the spectrum of existing international management and regulatory techniques to the practical solution of scientific and technological problems requiring international action, and suggests circumstances and conditions under which these techniques might be applied toward the resolution of specific technology-related transnational policy issues.

Anderson, D.M., Crowder, W.K., Gatto, L.W., Haugen, R.K., and Marlar, T.L., **An ERTS view of Alaska, a regional analysis of earth and water resources based on satellite imagery**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-TR-241, June 1973, 101 pp.

A preliminary study has been made of the value of satellite imagery in synoptic surveys of the distribution and environmental interrelationships of permafrost terrain and of coastal sedimentation and related processes in Cook Inlet, Alaska. Earth Resources Technology Satellite multispectral scanner (MSS) imagery was the primary data source for this investigation. Aerial underflight imagery and ground observations of selected sites were secondary data sources. Emphasis has been placed on evaluating the feasibility of mapping permafrost terrain from textural and tonal patterns related to surficial geology and vegetation. A mosaic of a 153,400-sq. km. area in north-central Alaska has been prepared at a scale of 1:1 million. Seven surficial geology, eight vegetative cover, and four permafrost terrain units were defined and delineated. Many geomorphic features were also recognized: thaw lakes, stream drainage patterns, glacial moraines, cirques, abandoned glacial valleys, and

volcanic cones. Preliminary analysis of the regional hydrologic and oceanographic processes in Cook Inlet has been accomplished. It is evident that the distribution of sediments and regional circulation patterns can be monitored using satellite imagery.

Anderson, D.M., Crowder, W.K., Gatto, L.W., Haugen, R.K., Marlar, T.L., and McKim, H.L., **Applications of ERTS-1 imagery to terrestrial and marine environmental analyses in Alaska**, *Earth Resources Technology Satellite-1 Symposium (3rd)*, Washington, D.C., 1974, Vol. 1: Technical presentations, Section B, pp. 1575-1606, 32 refs.

ERTS-1 imagery provides a means of distinguishing and monitoring estuarine surface water circulation patterns and changes in the relative sediment load of discharging rivers on a regional basis. The interpretation of geologic and vegetation features resulted in preparation of improved surficial geology, vegetation, and permafrost terrain maps at a scale of 1:1 million utilizing ERTS-1 Band 7 imagery. This information will be further utilized in a route and site selection study for the Nome to Kobuk Road in central Alaska. Large river icings along the proposed Alaska pipeline route have been monitored. Sea ice deformation and drift northeast of Point Barrow, Alaska, has been measured during a four-day period in March and shorefast ice accumulation and ablation along the west coast of Alaska is being mapped for the spring and early summer seasons. These data will be used for route and site selection, regional environmental analysis, identification and inventory of natural resources, land use planning, and in land use regulation and management.

Anderson, D.M., Gatto, L.W., Haugen, R.K., Marlar, T., and Slaughter, C.W., **Arctic and subarctic environmental analyses utilizing ERTS-1 imagery**, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Bimonthly progress report No. 1, August 1972, 3 pp.

This article pertains to earth resources technology satellite A, imagery, Alaska, arctic regions, aerial photography, photointerpretation, densitometers, data acquisition, data processing, and simulation.

Anderson, D.M., Gatto, L.W., Haugen, R.K., and McKim, H.L., **Cold regions environmental analysis based on ERTS-1 imagery**, *International Symposium on Remote Sensing of Environment (8th)*, Proceedings, October 1972, 12 pp., 15 refs.

An overriding problem in arctic and subarctic environmental research has been the absence of long-term observational data and sparseness of geographical coverage of existing data. Studies of synoptic environmental events over regional-size areas have been either impossible or prohibitively expensive. The launching of ERTS-1 on 23 July 1972, provides for the first time a means of accomplishing many types of investigations that were not feasible previously. Presented here is an analysis of the Upper Koyukuk-Kobuk River area located in NW Alaska. The image analyzed (1003-21355-457) is a color composite made from data acquired in the green, red, and infrared bands of the multispectral scanner. The area is devoid of cultural features except for several small villages and brush airstrips near the rivers. Documented information on the environment of the area is limited, consisting largely of statewide coverage of geology, vegetation, permafrost, and climate. Therefore, a substantial challenge is provided in the interpretation of regional permafrost distribution and regimes in Alaska.

Apel, J.R., **Synopsis of SEASAT-A scientific contributions**, United States National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratories, Miami, Florida, Collected reprints, Vol. 1, September 1976, pp. 93-103, refs.

The SEASAT-A Mission is a key element of the NASA Earth and Ocean Physics Application Program. It is expected to make major contributions to ocean science and to lead to a number of significant advances in the study of the atmosphere and the solid Earth. SEASAT-A should reveal the principal features of the dynamic behavior of the ocean gravity waves, wave heights, wave directional spectra, wave images, sea surface temperature, ice fields and leads, tides and currents, surface winds, and the planetary atmosphere.

Arcese, R., Hlavka, D.L., and Sabatini, R.R., **Applications of the Nimbus 5 ESMR to rainfall detection over the oceans and to sea-ice detection**, Earth Satellite Corporation, Washington, D.C., Environmental Prediction Research Facility (Navy), Monterey, California, Naval Regional Procurement Office, Oakland, California, Contract No. N66314-73-C-1572, April 1975, 80 pp.

The report explores the applicability of the Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) to rainfall detection over the oceans and to sea ice detection. Two different but complementary approaches are taken - a theoretical approach, which involved the theoretical calculations of brightness temperature (t sub b) in a prepared scenario of model atmospheres and surface conditions, and an empirical approach, which made use of simultaneous measurements of our parameters of interest from other sensors: WSR-57 radar for precipitation, and images from other satellites (NOAA and LANDSAT) for sea-ice.

Barnes, J.C., Chang, D.T., and Willand, J.H., **Application of ITOS and Nimbus infrared measurements to mapping sea ice**, Allied Research Associates, Inc., Baltimore, Maryland, Report No. ARA-

8G93-F, June 1972, 95 pp.

The application to ice mapping of recently available ITOS and Nimbus thermal infrared data is investigated. The ITOS-1 Scanning Radiometer (SR) and the Nimbus-4 Temperature-Humidity Infrared Radiometer (THIR) have been the first satellite high resolution sensors to operate in the 10.5-12.5 micrometers spectral interval. In this study, arctic ice distributions are mapped from ITOS Direct Readout (DRSR) imagery; densitometric analyses are performed using DRSR and Nimbus imagery; ITOS digitized temperatures are mapped through the 5-level scheme developed in previous studies; and the use of Nimbus daytime IR data is evaluated.

Barnes, J.C., Chang, D.T., and Willand, J.H., **Use of satellite high resolution infrared imagery to map arctic sea ice**, Allied Research Associates, Inc., Concord, Massachusetts, Report No. ARA-8G60-F, August 1969, 115 pp.

The report presents an evaluation of High Resolution Infrared (HRIR) imagery from the Nimbus I and II satellites for mapping arctic sea ice. Included are investigations to determine the type of ice feature identifiable in these data, the limiting size of features that can be reliably detected, and the application of HRIR imagery for sea ice surveillance. The major part of the evaluation is devoted to analysis of nighttime HRIR data in the real-time, film-strip format. To assist in the interpretation of the film strips, full-resolution digitized data are analyzed. A sample of daytime measurements from Nimbus II is also examined.

Battikha, M., Brake, L., and Wedler, E., **Shoe Cove satellite data assistance to Canada's cold ocean resource development**, Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland, St. John's, Publication 78-3, 1978, 16 pp., refs.

The Shoe Cove Satellite Receiving Station, a facility of the Canada Centre for Remote Sensing and the Federal Dept. of Energy, Mines, and Resources, is located 25 km N of St. John's, Newfoundland. The system can track, receive, and process signals from four satellites and process them electronically and photographically. Sea surface temperatures are accessible daily with related information to fishery activities, iceberg deterioration, freezing spray warnings, and sea ice break-up predictions. Information on sea ice distribution is applied to locating areas of higher biological activity in ice and strategic vessel routing assistance. Shoe Cove data on iceberg/ocean vessel detection can be applied to the cataloguing of icebergs and ocean vessels, iceberg hazard prediction, and iceberg drift limits and deterioration.

Bilello, M.A., **Surface measurements of snow and ice for correlation with aircraft and satellite observations**, NTIS #AD-689 449, May 1969, 9 pp. 14 refs.

The seasonal extent of the earth's snow and ice cover can easily be determined by aircraft and satellite reconnaissance. However, determination of the depth and physical properties of the snow cover and the thickness of ice on lakes, rivers, and along coastlines by these remote sensors is in an early state of development. Correlation of the remote sensing data with actual surface conditions could be accomplished through use of an existing network of snow and ice stations located throughout North America. This network, comprising over 100 stations, is maintained by U.S. Army Terrestrial Sciences Center (USA TSC) in cooperation with other government agencies and accumulates the most extensive and reliable data for such correlation studies.

Booda, L.L. and Johnson, J.D., **Spacecraft oceanography: ocean scientists finally have a satellite to call their own**, *Sea Technology*, Vol. 19, No. 10, October 1978, pp. 10-15, no refs.

Satellite data are increasingly aiding research work on waves, winds, tides, currents and their meanders, internal waves, ice floes, icebergs, ice coverage, shallow bottom photography, and temperatures. Sensors utilize a broad portion of the electromagnetic spectrum - UHF, microwave, centimeter and millimeter waves, IR, far IR, the visible spectrum. The history and development of weather observation and oceanographic work in conjunction with satellite developments -including such satellite series as the GOES, TIROS, ESSA, NOAA, Nimbus, and LANDSAT - are given. SEASAT A, launched June 26, 1978, in a polar orbit, is the first satellite dedicated to oceanographic research and development. It presently measures surface winds, sea state, sea-surface topography, wave ht, wave spectra, sea ice conditions, sea-surface temperatures, and other conditions for use in weather and sea forecasting for shipping, oil industry, environmental, military, and other applications. SEASAT A was scheduled to assist in the First GARP Global Experiment and then become part of NOAA's NESS operations.

Brooks, R.L., **Monitoring of thickness changes of the continental ice sheets by altimetry**, *Journal of Geophysical Research*, Vol. 84, No. B8, July 1979, pp. 3965-3.968.

Radar altimeter measurements from the GEOS 3 satellite are being utilized to define the topography of the southern Greenland ice sheet between latitudes 60°N and 65°N. The resultant elevations have been correlated with two geoceiver sites on the ice surface; the agreement is within a few meters. The internal repeatability of the altimeter-derived elevations has been assessed at the crossovers of the satellite ground tracks; the observed agreements varied from 0.07 to 3.10 m, intervening times being 1 day and 674 days, respectively. Improved knowledge of the temporal

changes in the topographic expression of the continental ice sheets, via satellite altimetry, will significantly add to the understanding of glaciological and climatological processes.

Brown, R.J., **Remote sensing of the ocean, Part 1: physical, chemical, and geological properties**, National Technical Information Service, Springfield, Virginia, Vol. 2, June 1979, 108 pp., bibliography plus abstracts.

The studies describe remote sensing methods as they are applied to ocean temperature, sea ice, marine biology, and sound and light transmission. Techniques of measurement using radiometry, microwave spectroscopy, radar systems, infrared spectroscopy, and photography are described. These measurements are made from both aircraft and satellites. (This updated bibliography contains 99 abstracts, 24 of which are new entries to the previous edition.)

Campbell, W.J., **Dynamics of Arctic ice-shear zones**, United States Geological Survey, Washington, D.C., Professional paper 929, 1976, pp. 346-349.

The capacity of ERTS imagery to provide information on the morphology and dynamics of the ice-shear zones is described with successive ERTS-1 images of a section of the northwest coast of Banks Island, Northwest Territories, Canada. These photographs show the successive changes in the following three distinct zones of ice: 1) the shore lead in which frazil ice (groups of needle-like crystals of ice) and grease ice (ice slush) are forming; 2) a zone of recently formed gray ice approximately 20 km wide, which is probably 20-30 cm thick; and 3) large consolidated floes of first-year ice, which are probably 1.5 m thick.

Campbell, W.J., Gloersen, P., Ramseier, R.O., and Weeks, W.F., **Geophysical studies of floating ice by remote sensing**, *Journal of Glaciology*, Vol. 15, No. 73, 1975, pp. 305-328, 54 refs.

This paper presents an overview of recent remote-sensing techniques as applied to geophysical studies of floating ice. The current increase in scientific interest in floating ice has occurred during a time of rapid evolution of both remote-sensing platforms and sensors. Mesoscale and macroscale studies of floating ice are discussed under three sensor categories: visual, passive microwave, and active microwave. The specific studies that are reviewed primarily investigate ice drift and deformation, and ice type and ice roughness identification and distribution.

Campbell, W.J., Ramseier, R.O., Weaver, R.J., and Weeks, W.F., **Skylab floating ice experiment final report**, U.S. National Aeronautics and Space Administration, Report No. NASA-CR-147446, December 1975, 67 pp.

Coupling of the aircraft data with the ground truth observations proved to be highly successful with interesting results being obtained with IR and SLAR passive microwave techniques, and standard photography. Of particular interest were the results of the PMIS system, which operated at 10.69 GHz with both vertical and horizontal polarizations. This was the first time that dual polarized images were obtained from floating ice. In both sea and lake ice, it was possible to distinguish a wide variety of thin ice types because of their large differences in brightness temperatures. It was found that the higher brightness temperature was invariably obtained in the vertically polarized mode, and as the age of the ice increases the brightness temperature increases in both polarizations. Associated with this change in age, the difference in temperature was observed as the different polarizations decreased. It appears that the horizontally polarized data is the most sensitive to variations in ice type for both fresh water and sea ice. The study also showed the great amount of information on ice surface roughness and deformation patterns that can be obtained from x-band SLAR observations.

Campbell, W.J., **Visual observations of floating ice from Skylab**, United States National Aeronautics and Space Administration, Washington, D.C., Report No. NASA-SP-380, 1977, pp. 353-379, refs.

The lake and sea ice visual observation experiment performed during the Skylab-4 mission was very successful. In the initial experiment design, the Gulf of St. Lawrence and Lake Ontario were chosen as prime sites at which ground-truth measurements and aircraft remote sensing data were to be obtained. In addition, the Skylab-4 astronauts obtained excellent photographs of sea ice in the Sea of Okhotsk and in the James Bay portion of Hudson Bay and of icebergs in the Southern Ocean. Some of the sequential photographs contain useful broad-scale information on the distribution of ice and ice types, the overall deformation patterns, and the amount of relative ice motion. Skylab-4 results show that the presence of man in space is vital for certain observational tasks. Man has the ability to select and focus on ice areas that show a high degree of activity and to choose the period and extent of experimental observations.

ECON, Inc., **SEASAT economic assessment, Volume 6: Arctic operations case study and generalization**, Princeton, N.J., Report No. NASA-CR-148499 and REPT-75-125-6B-V-6, 31 August 1975, 77 pp.

The hypothetical development and transportation of Arctic oil and other resources by ice breaking super tanker fleets to the continental East Coast are discussed. The utilization of SEASAT ice mapping data is shown to contribute to a more effective transportation operation through the Arctic ice by reducing transportation costs as a consequence of reduced transit time per voyage.

Forsyth, D. and McMillan, M.C., **Satellite images of Lake Erie ice: January -March 1975**, National Environmental Satellite Service, Washington, D.C., Report No. NOAA-TM-NESS-80, June 1976, 22 pp.

The NOAA-4 environmental satellite provides daily images of portions of Earth in the visible (0.6 to 0.7 micrometer) and thermal (10.5 to 12.5 micrometer) spectral regions from a Very High Resolution Radiometer (VHRR) having approximately 1-km resolution. This improved resolution has permitted more detailed observations of Great Lakes ice than was possible with the previous generation of operational satellites. Both visible and infrared imagery are presented to show ice formation and dissipation in Lake Erie and vicinity. Coverage begins on January 21 and ends on March 18, 1975. Only cloudfree or partly cloudy imagery is included.

Forsyth, D.G., McGinnis, D.F., and Wiesnet, D.R., **Selected satellite data on snow and ice in the Great Lakes basin, 1972-73 (IFYGL)**, *Conference on Great Lakes Research (17th)*, McMaster University, Hamilton, Ontario, 12-14 August 1974, Proceedings, Ann Arbor, Michigan, International Association for Great Lakes Research, 1974, Part 1, pp. 334-347, refs.

Three snow-extent maps of the Lake Ontario drainage basin were prepared from the NOAA-2 satellite, visible band images during the IFYGL (1972-1973). These maps are discussed, and the satellite data are evaluated for snow-extent mapping. The value of ERTS-1 imagery and digital data is also discussed in relation to the Lake Ontario basin studies. ERTS-1 MSS data are excellent for ice identification and analysis, but are not useful for forecasting where timely receipt of data is imperative. NOAA-2 VHRR data are timely, but the lower resolution of the VHRR makes identification of certain ice features difficult. NOAA-2 VHRR is well suited for snow-extent maps and thermal maps of large areas such as the 19,000-km, SUPER 2, Lake Ontario basin.

Gloersen, P. and Zwally, H.J., **Passive microwave images of the polar regions and research applications**, *Polar Record*, Vol. 18, No. 116, May 1977, pp. 431-450, 30 refs.

This paper presents some examples of recent microwave images of the north and south polar regions, reviews the physical basis for the measurement of certain desired parameters, and discusses the significance of some of the glaciological, oceanographic, and meteorological observations that have been made. In addition to an introduction, sections are provided on microwave emissivity and brightness temperature polar microwave images, sea ice and icebergs, ice sheets, ice shelves, and ice caps land, snow cover, lakes, and developing applications. Continuing efforts to assemble systematically data of controlled quality for dissemination and further scientific study are also noted. Although the scope of the paper is mainly limited to the single-frequency (1.55 cm wavelength) observations by the Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR), future multifrequency applications are discussed briefly.

Grabham, A.L. and Sherman, J.W., III, **Skylab earth resources experiment package experiments in oceanography and marine science**, National Environmental Satellite Service, Spacecraft Oceanography Group, Washington, D.C., Report No. NOAA-TM-NESS-51, September 1973, 81 pp.

The paper was prepared to provide a reference for marine scientists for coordination and exchange of information in connection with the SKYLAB Earth Resources Experiment Package (EREP) missions of 1973. The experiments planned, the experiment package used, the methods for handling data, and the schedule for ships for potential ocean ground truth data are listed and described.

Hibler, W.D., III, Tucker, W.B., and Weeks, W.F., **Measurement of sea ice drift far from shore using LANDSAT and aerial photographic imagery**, *International Symposium on Ice Problems (3rd)*, Hanover, New Hampshire, 18-21 August 1975, Proceedings, International Association of Hydraulic Research, 1975, pp. 541-554, 6 refs.

This paper discussed recent work on the development of analysis procedures for obtaining drift and deformation measured from sequential visual imagery of sea ice that is located far from land. In particular for LANDSAT images far from land a semi-automatic procedure for transferring the location coordinates of a common set of ice features from the Earth coordinate system of one image to another is discussed. Necessary inputs for the transfer are the location coordinates (latitude and longitude) of the center of each image and the location of two arbitrary points on a known line of longitude; all this information is available from LANDSAT, although with some error. These errors will produce spurious apparent strains if velocities are estimated by simply taking position differences. With regard to measuring strain from sea ice aerial imagery without ground control, errors in such measurements are examined using uncorrected photographs. The errors in using such uncorrected imagery and using common undeformed ice floes to establish a common scale are found to be of the order of 1% whereas typical maximum differential motions are as large as 5%.

Hibler, W.D., III, Tucker, W.B., and Weeks, W.F., **Techniques for studying sea ice drift and deformation at sites far from land using LANDSAT imagery**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, November 1975, 18 pp.

A semi-automatic procedure for transferring the location coordinates of a common set of ice features from the Earth coordinate system of one LANDSAT image to another is discussed. Errors in the transferral technique are examined using imagery over land and are found to be dominated by deviations (as large as 8 km) in the actual position of the center of the image from its stated position. A least squares strain program, which utilized polar coordinates to eliminate spurious effects that may occur if the coordinate system of a given flow is used as the common coordinate system, is discussed. Errors in coordinate system rotation, center location, distortions, and nonlinearities in the images caused errors in vorticity of the order of 0.5% and in strain of the order of 0.1% per day. Both these errors are less than typical sea ice vorticity and strain rate.

Hibler, W.D., III, Tucker, W.B., and Weeks, W.F., **Techniques for using LANDSAT imagery without references to study sea ice drift and deformation**, *AIDJEX Bulletin*, No. 31, March 1976, pp. 115-135, 12 refs.

A semi-automatic procedure is described for transferring ice coordinates rapidly and accurately from one LANDSAT image to another and for simultaneously estimating all linear measures of the ice deformation. The procedure takes into account the nonparallel nature of the longitude lines and the finite curvature of the latitude lines, factors which are particularly critical in the polar regions. Necessary inputs are the location coordinates (latitude and longitude) of the center of each image and the location of two arbitrary points on a line of longitude on the image. These equations, which are valid over distances of several hundred kilometers, bypass the complex and time-consuming procedure of projecting points on the spheroid. After the transfer of common ice feature locations (on successive days) is completed, a least-squares program yields the average strain rate and vorticity, with the strain rate being independent of errors in the transfer of the coordinate system. Transfer, vorticity, and strain rate errors of the technique are described.

Jayaweera, K.O.L.F., **Use of enhanced infrared satellite imagery for sea ice and oceanographic studies**, *Ocean Engineering*, Vol. 3, 1976, pp. 293-298.

Infrared (i.r.) imagery from the NOAA 2, 3, and 4 satellites could be used to measure accurately the absolute temperature of the sea surface and sea water. Comparison with measured temperatures indicate that the satellite observed values are within 2°C of those measured. Contouring temperatures and observing temperature fluctuation within 0.5°C is also possible by enhancing the infrared image. This is done by assigning the 16 steps of gray of the image to a desired small temperature scale. The existence of open water areas within the pack ice and the positions of the ice edges could be readily distinguishable by generating special imagery in such a way that the gray scale covers two temperature ranges with a gray tone jump at the freezing point of sea water. In this way, the ice-water boundary appears as a line of demarcation between two different gray tones. Because the i.r. imagery is available all year round, these techniques are readily applicable at all times especially during the winter months when the low sun angles make visible imagery not useful.

Kaminski, H., **Remote sensing of variations of sea-ice-surfaces in the Barents Sea from 1966-1975 by means of satellite data, among others NOAA-VHRR**, *International Polar Meeting (10th)*, Zurich, 6-8 April 1976, 32 pp.

The sea ice dynamics were investigated from ESSA 2, 4, 6, 8, ITOS 1, NOAA 1, 3, and 4 satellite infrared sensor measurements in April of the years 1966 to 1975. The free water surface was established and correlated with the average air and water temperature measured at the Vardoe, Kanin, Bjoernoya, Spitzbergen, and Ostrov Heisja weather stations. The free water surface is shown to have increased in the reference period, and the annual variations of the free water surface show a good correlation with the average water temperature of the Gulf North Cape stream and with the average April air temperature.

Kovacs, A., McKim, H.L., and Merry, C.J., **Islands of grounded ice**, *Arctic*, Vol. 28, No. 3, September 1975, pp. 213-216, 10 refs.

The report demonstrates the usefulness of ERTS-1 imagery for locating and identifying islands of grounded ice. Several examples are cited.

Kunzi, K.F., **Snow and ice surfaces measured by the Nimbus-5 microwave spectrometer**, *Journal of Geophysical Research*, Vol. 81, No. 27, 20 September 1976, pp. 4965-4980, refs.

The 22.2- and 31.4-GHz channels of the microwave spectrometer onboard the Nimbus-5 Earth observatory satellite provide information about the global distribution and character of various types of snow and ice. Observations for the winter and summer of 1973 are presented for both polar regions. Well defined spectral signatures are found for snow, sea ice, and land ice in Greenland and Antarctica. A simple model with subsurface temperature gradients in a lossy homogeneous dielectric does not account for the observations; internal scattering effects appear to play a dominant role.

LeSchack, L.A., **Potential use of satellite IR data for ice thickness mapping**, Development and Resources Transportation Co., Silver Spring, Maryland, National Environmental Satellite Service, Washington, D.C., Final report, March 1975, 32 pp.

An approach to automated mapping of the thickness and movement of Arctic ice by means of statistical examination of NOAA VHRR satellite IR data is discussed. In previous work a useful empirical relationship was observed: airborne or satellite radiant temperature measurements of sea ice are proportional to the thickness of the ice, have normal distributions, and the areas beneath the distribution curves are proportional to the surface area of the pack ice types from which they were derived. In the present work, substantially more data have been examined so that it is now possible to outline the basic steps for implementing an algorithm to automate ice mapping. Five passes made by NOAA-2 and NOAA-3 satellites were used for the analysis. These passes provided radiant temperature data of the Beaufort Sea ice during January, February, March, April, and May 1974. Examination of the shapes of the temperature distribution histograms derived from the data suggested differences that could be delineated by simple statistical techniques.

McClain, E.P., **Applications of environmental satellite data to oceanography and hydrology**, National Environmental Satellite Center, Washington, D.C., Report No. NESCTM-19, January 1970, 19 pp.

A research group within the National Environmental Satellite Center is helping to develop applications of environmental satellite data to problems in oceanography and hydrology. Techniques for large-scale mapping of sea surface temperatures in clear and partly cloudy regions are being developed with the aid of high-resolution infrared (HRIR) data from NASA's Nimbus satellites. Digitized television pictures from the ESSA operational satellites and NASA's Applications Technology Satellites (ATS) are being studied in conjunction with the relation between sunglint patterns and the ocean wave spectrum and low-level wind stress. New methods for the mapping of major snow and ice boundaries from satellite altitude have been devised and are being tested. The NESC is also involved cooperatively with several government agencies and NASA in research and applications development in conjunction with the first Earth Resources Technology Satellites (ERTS).

McClain, E.P., **Potential value of earth satellite measurements to oceanographic research in the Southern Ocean**, National Environmental Satellite Service, Washington, D.C., Report No. NOAA-TM-NESS-61, January 1975, 23 pp.

Data from National Oceanic and Atmospheric Administration (NOAA) operational satellites as well as from National Aeronautics and Space Administration (NASA) research and development satellites such as Nimbus and the Earth Resources Technology Satellite (ERTS) have increasing operational and research use in oceanography. Methods are being developed to improve the mapping and monitoring of icepack concentration, character, and condition from satellite observations in the visible, near-infrared, and thermal infrared parts of the spectrum. Techniques also have been developed to map sea-surface temperatures and temperature gradients on regional and hemispheric scales from space. Recently acquired NOAA and ERTS measurements are higher in spectral and spatial resolution than those previously available, and the newest Nimbus carries the first passive microwave imager in space. Examples of some of this newly available data and their applications are presented, and a brief discussion of future sensor systems expected to be of interest to Southern Ocean researchers is given.

McClain, E.P., **The use of infrared and visible imagery for sea ice monitoring**, National Environmental Satellite Service, Washington, D.C, 1978, 34 pp.

Global mapping of pack ice conditions and the climatic roles of ice are dealt with along with the presentation of information on visible and infrared observations from spacecraft and aircraft. Historical ice records are identified in an appendix.

McGinnis, D.F., Jr., and Schneider, S.R., **Monitoring river ice breakup from space**, *Photogrammetric Engineering and Remote Sensing*, Vol. 44, No. 1, Washington, D.C., January 1978, pp. 58-68, refs.

Visible images from operational environmental satellites provide an effective means to assess formation and dissipation of river ice. The National Environmental Satellite Service (NESS) receives 1-km resolution images daily from polar-orbiting NOAA satellites and every 30 min during daylight from NOAA geostationary satellites. During the period 4-14 April 1976, 14 ice-covered reaches on the Ottawa River between Lake Timiskaming and Montreal were monitored daily by using imagery from NOAA-4 and GOES-1 satellites. The ice-covered reaches were observed to break up in place; at the end of the 10-day study period, only three of the original 14 remained. Satellite views of the river permitted the measurement of changes in the length of the individual ice-covered reaches. High-resolution imagery from NASA's LANDSAT satellites and digital tape data from the NOAA polar-orbiting satellites were used to calibrate the measurements from the operational imagery.

McGinnis, D.F., **Satellite detection of melting of Environment (8th)**, 2-6 October 1972, University of Michigan, Ann Arbor, Proceedings, April 1973, pp. 231-240, refs.

Use of near-IR data, in conjunction with reflected visible radiation, appears to permit detection of melting snow and ice. Under normal conditions, snow and ice are highly reflective in both the visible and near-IR areas of the electromagnetic spectrum. Under melting

conditions, however, near-IR radiation is strongly absorbed, whereas visible radiation is strongly reflected. Comparison of simultaneous visible and near-IR imagery from the Nimbus-3 satellite provides a method for monitoring the melting of snow and ice that may be applied to snowpack-runoff prediction, flood forecasting, and lake navigation. Several examples - the Sierra Nevada, Lake Winnipeg, the Alps, and northwest Canada - are provided to illustrate the use of this spectral difference.

Mitchell, P.A., **Aerial ice reconnaissance and satellite ice information microfilm file**, Naval Oceanographic Office, Washington, D.C., Report No. NOO-RP 17, August 1976, 37 pp.

Interest in the polar regions has increased manyfold in recent years principally due to the newly developing economic incentives and revived military significance of the Arctic and the continuing scientific research in the Antarctic. Improvement and further development of operational sea ice forecasting techniques that allow our naval forces to operate safely in these areas depend heavily upon the maintenance of historical ice data files. The Aerial Ice Reconnaissance and Satellite Ice Information Microfilm File effectively substitutes for the terminated Oceanographic Office annual reports of the arctic and antarctic ice observing and forecasting programs. This publication provides the researcher with listing of available microfilm in one of the Navy's more extensive ice data files and describes the procedures to follow to obtain copies of the original chart analyses of aerial ice reconnaissance and satellite ice data.

Naval Oceanographic Office, **Spacecraft oceanography project**. Annual report 1, Washington, D.C., 1 September 1966, 259 pp.

The Spacecraft Oceanography Project (SPOC) was established within the U.S. Naval Oceanographic Office (NAVOCEANO) on 8 October 1965. Since this time the major efforts of SPOC have been directed towards the formulation and implementation of a clearly defined spacecraft oceanographic program. Entailed in this activity is the need for creation of experiment programs, the requirement to conduct various feasibility studies, and the necessity for stimulating interest from within the oceanographic community. The intent of this Annual Report is to provide an overall review of the past and current efforts that have been and are continuing to be applied to this program. The report covers the main areas of investigation, including description of remote sensors and their requirements, types of probable oceanographic experiments, and aircraft and spacecraft testing requirements. Detailed program plans are presented that outline current and future tasks associated with the logical pursuit of this program to completion. Funding and schedules for implementation of these plans are also discussed. The technical advantages of using Earth-orbiting spacecraft to measure significant oceanographic phenomena are described in detail along with economic benefits to be derived from this technological application.

Needham, S., Nelson, H., and Roberts, T.D., **Sea ice reconnaissance by satellite imagery**, University of Alaska, College Institute of Arctic Environmental Engineering, Final report, June 1970, 56 pp.

The effectiveness of Nimbus I Advanced Vidicon Camera System (AVCS) imagery for mapping Arctic sea ice is investigated in this report. A world-wide polar ice pack boundary, mapped solely from Nimbus I data, is presented. Numerous comparisons are made between ice conditions deduced from Nimbus I AVCS and other data sources and it is concluded that an AVCS imagery is highly effective for mapping detailed ice conditions on a week-to-week basis even under relatively poor weather conditions.

Rothrock, D.A., **Testing the redistribution of sea ice thickness from ERTS photographs**, *AIDJEX Bulletin*, No. 29, University of Washington, Seattle, July 1975, pp. 1-19, refs.

Measurements of strain and fractional area changes of thin ice in sequential ERTS photographs of sea ice are used to test a hypothesized mathematical description of the production of open water and the redistribution of thin ice into thick by ridging. It is found that both these processes occur to a lesser degree than had been previously assumed. Consequently, the yield curve for plastic flow of pack ice is comparatively thin. Also, the amount of thin ice involved in ridging is probably about 5%.

Wendler, G., **Sea ice observation by means of satellite**, *Journal of Geophysical Research*, Vol. 78, No. 9, 20 March 1973, pp. 1427-1448.

For a small area (about 120 km x 150 km) of the Arctic Ocean off the shore of north Alaska the ice conditions were examined in detail by satellite imagery. Instead of using 64 steps of gray, 15 brightness steps were distinguished by computer for each data point. To suppress the transient cloudiness, minimum brightness composites were used. The ice conditions could be drafted in great detail for 5-day periods for the summer of 1969, this fact showing the value of satellites as a unique tool for sea ice reconnaissance. The conditions were found to depend strongly on the wind direction. Offshore wind moved the ice out, and wind toward the shore brought it back. A good correlation was found with the wind taken from the weather maps, although the data from a ground-based climatological station were not always in good agreement with the ice movement, probably because of orographic effects. A comparison with ice charts mapped by more conventional methods showed good agreement in most cases. The satellite picture, however, gave much greater detail. Monthly mean albedo maps were

constructed from the brightness composites for the 4 months from mid-May to mid-September and compared with previous measurements.

## B. Airborne

Ackley, S.F. and Keliher, T.E., **Ice sheet internal radio-echo reflections and associated physical property changes with depth**, *Journal of Geophysical Research*, Vol. 84, No. 10, September 1979, pp. 5675-5680.

The use of radio-echo sounding records to indicate the presence of internal layers within large ice sheets is of interest to glaciologists because it offers a possible means of tracking the internal properties of the ice sheets over large distances. In this paper we use the measured physical properties of core to bedrock taken at Cape Folger, East Antarctica (66°22"S, 111°E, 324 m depth), to compute a depth-reflection coefficient profile for comparison with the observed radio-echo reflections. The measurements available on physical properties are density variations, bubble size and shape changes, and crystal fabric variations. In calculations to differentiate the effects of the physical properties, it appears that density variations account for the primary contributions to the calculated dielectric property changes corresponding to the highest observed reflection coefficients. However, bubble changes alone can also account for reasonable, though lower, reflection coefficients at the depths corresponding to observed reflections. Crystal fabric variations correspond poorly with the reflection locations. The close correspondence between the depths of the bubble shape changes (which are definitely deformational features) and the depths of the density variations, and between both of these and the radio-echo layers, indicates that deformational events in the ice sheet's history are represented by the variations in physical properties and associated radio-echo records.

Adey, A.W. and Reed, G.N., **Radio-frequency radiometry as a remote sensing technique in maritime reconnaissance and marine sciences in a northern environment**, Communications Research Centre, Ottawa, Report No. CRC-TN-660, September 1973, 22 pp.

The application of the RF radiometry technique to the general maritime reconnaissance and marine sciences role in the Canadian North is discussed. Results of tests carried out with a helicopter-borne, multichannel, UHF radiometer in August 1972 in the Hudson Strait and Labrador Coast areas are included. Radiation data were obtained during flights over ships, ocean and fresh water, pack ice, icebergs, glaciers, and land features. These initial results were encouraging in demonstrating the potential of the technique, not only in direct support of maritime operations through aiding in detection and identification of features of interest, but with possible application in areas such as hydrology and glaciology.

Adey, A.W., Barrington, R.E., Hartz, T.R., Mather, W.E., and Rolfe, W., **Theory and field tests of a UHF radiometer for determining sea ice thickness**, Communications Research Centre, Ottawa, Report No. CRC-TN-637, January 1972, 17 pp.

A theoretical analysis of the UHF emissions from sea ice and/or sea water is outlined. This work indicates that a radiometer system designed to observe these emissions could be used to determine the thickness of sea ice. To explore this possibility, a radiometer operating at frequencies from 400 MHz to 2.3 GHz was designed and built. The results of initial ground-based and airborne tests of this instrument are presented. Comparisons are made between the field observations and the theory.

Anderson, V.H., **High altitude, side-looking radar images of sea ice in the Arctic**, *Symposium on Remote Sensing of Environment (4th)*, Proceedings, University of Michigan, Ann Arbor, 12-14 April 1966, pp. 845-857.

High altitude, side-looking radar was used to image sea ice patterns between Greenland and Ellesmere Island and within the Arctic Ocean, during the spring of 1962. Concurrent low altitude visual reconnaissance of sea ice patterns was conducted by the author over much of the same flight path flown by the radar aircraft. A comparison of the radar patterns with actual observed and photographed sea ice conditions is presented in this paper. A dramatic example of the eroding processes of polar ice as it moves southward to warmer environments is displayed by the radar imagery and is discussed in this paper. An example of radar imagery of sea ice in the Arctic Ocean, existing under a deteriorating environment during the summer of 1962, is also presented. Included is the radar image of Ice Island "T3" in the Beaufort Sea, north of Alaska.

Anderson, V.H., **Preliminary studies of infrared imagery of sea-ice patterns**, NTIS #AD-334 048, October 1962, 13 pp., 5 refs.

This report demonstrates the value of airborne infrared scanner imagery as an aid in determining some of the physical characteristics of sea ice. It contains an interpretation of some infrared scanner imagery of sea-ice patterns that existed in Baffin Bay near Thule, Greenland, in December 1960. It also outlines a program to further the study of sea ice by using various airborne sensing devices sensitive to different portions of the electromagnetic spectrum.

Anderson, V.H., **Radar imagery of arctic pack ice, Kane Basin to North Pole**, NTIS #AD-721 901, April 1968, 31 pp.

The pictorial brochure has been compiled to show an existing radar system's capability of imaging large areas of sea ice in relative short periods of time. The radar imagery was obtained during the latter part of April 1962 by a USAF high-altitude reconnaissance aircraft equipped with a side-looking scanner-type radar unit. USA CRREL personnel made visual aerial

observations of the ice imaged by radar, utilizing USN ice reconnaissance aircraft active in the area during this period. Conventional hand-held aerial photography of the ice characteristics was obtained on these flights and some of these photographs are included to supplement the radar imagery.

Bay, A., Biache, A., Bradie, R.A., Mann, C., and Peppard, C., **Data reduction of airborne sensor records**, Raytheon Corporation, Arlington, Virginia, Autometric Operation, Coast Guard, Washington, D.C, Office of Research and Development, Report No. FR-1385, July 1970, 210 pp.

The capabilities of four remote sensors - panoramic camera, thermal infrared scanner, laser profiler, and side-looking airborne radar - were examined to determine level of ice detail of code, individually and in combination. Textual descriptions of each sensor's ability to detect sea and fast ice conditions and phenomena are presented, along with photographic examples of ice types depicted on each sensor's record. Color illustrations reproduced in black and white.

Belousov, P.S., Bondarenko, I.M., Chelyshev, K.B., Loshchilov, V.S., and Zagorodnikov, A.A., **Two-dimensional statistical analysis of radar images of sea ice**, *Oceanology* (USA), Vol. 13, No. 2, 1973, pp. 287-96, 7 refs.

The theoretical principles and the procedure for obtaining the morphometric characteristics of sea ice from the results of a radar ice survey are described. The method is based on the optical, two-dimensional Fourier transform of a small-scale radar image of ice in the rays of a coherent light source (laser). Analysis of the spatial spectra of images thus obtained permits determining the statistical characteristics of the elements of the ice cover (average floe dimension, dispersion, size distribution of floes, and the correlation function). Examples of the optical processing and spectral analysis of radar images of different parts of an ice cover are examined. It is demonstrated that the optical method permits operational statistical analysis of ice images obtained with a "Toros" type side-looking radar set.

Betin, V.V., Uralov, N.S., and Zhadrinskii, S.V., **On the method of observations on sea ice from aircraft**, Naval Oceanographic Office, Washington, D.C., Report No. N00-Trans-123, 1961, 20 pp., Translation of Gosudarstvennyi Okeanograficheskii Institut., *Trudy* (USSR), No. 40, 1957, pp. 147-155, by M. Slessers.

The perspective angle instrument used for determining the location of aircraft, its direction and speed, as well as the observed ice objects, their size, contours, and concentration is described, pointing out the essential parts of the instrument and their operation. Further, the testing of the instrument and the observation data obtained with the aid of it are analyzed so as to present an objective evaluation of the advantages, and also of limitation, in the use of the instrument when carrying out serial ice reconnaissance.

Biggs, A.W., Fayman, D.L., Matreci, R., Moore, R.K., and Parashar, S.K., **Scatterometry techniques for sensing arctic sea ice thickness**, University of Kansas/Center for Research, Inc., Lawrence, Kansas, Report No. CRES-TR-185-12 and 13, November 1973, 326 pp.

Investigation of radar discrimination of sea ice is presented. Radar scatterometer data at 75 and 2.25 cm wavelength obtained from NASA Earth Resources Aircraft Program Mission 126 were analyzed. The mission was conducted in April 1970 off the coast of Point Barrow, Alaska. The scatterometer data were separated into seven different categories of sea ice. Sea ice was categorized according to thickness and age. The radar scattering from sea ice is compared for different sea ice types. An analytical theory of scatter from sea ice was developed and is presented.

Brown, W.E., Jr. and Elachi, C., **Imaging and sounding of ice fields with airborne coherent radars**, *Journal of Geophysical Research*, Vol. 8, No. 8, 10 March 1975, pp. 1113-1119, 14 refs.

Airborne coherent radar observations of ice fields conducted in the last 4 years are presented and discussed. These observations contain radar imagery of glaciers in southeast Alaska, imagery of coastal and sea ice in northern Alaska and the Beaufort Sea, and sounding of layered continental ice in Greenland.

Brown, W.L. and Horvath, R., **Multispectral radiative characteristics of arctic sea ice and tundra**, University of Michigan, Ann Arbor, Institute of Science and Technology, Report No. 027980-2-F, July 1971, 72 pp.

Multispectral remote sensor data acquired from an aircraft in the vicinity of Barrow, Alaska, are analyzed and the results of the analysis are presented. The spectral, spatial, and temporal radiation characteristics measured directly by the calibrated sensors for a variety of targets are compared and discussed. These data are then extended and extrapolated with the aid of ground measurements in order to arrive at estimates of the radiative components of the total energy budget for these targets.

Bryan, M.L., Elachi, C., Fontain, A.G., and Weeks, W.F., **Differences in radar return from ice-covered North Slope lakes**, *Journal of Geophysical Research*, Vol. 83, No. 8, August 1978, pp. 4069-4073.

Comparisons are made between L and X band synthetic aperture radar images of frozen lakes on the North Slope of Alaska and ground truth observations

of the nature of their ice covers. It is shown that the differences in radar backscatter observed on different areas of a lake can be correlated with whether or not the lake is frozen completely to the bottom at the site in question. This explanation is reasonable inasmuch as the reflection coefficient associated with the high-dielectric contrast ice/water interface is significantly higher than that associated with a low-contrast ice/-soil interface. However, the presence of the ice/water interface cannot be the only condition required for the higher backscatter because the ice/water interface per se would be specular at X and L band frequencies, causing the energy returned from the interface to be reflected away from the radar receiver. The other principal factor contributing to the return of energy from the ice/water interface to the receiver is believed to be the presence in the ice of numerous vertically elongated air bubbles, which would act as scatters.

Campbell, K.J. and Orange, A.S., **A continuous profile of sea ice and freshwater ice thicknesses by impulse radar**, *Polar Record*, Vol. 17, No. 106, 1974, pp. 31-41.

For several years, Geophysical Survey Systems, Inc. has been using an impulse radar system as a shallow subsurface exploration tool for engineering applications. Recently this system has been applied to the measurement of ice thickness both on sea-water and fresh-water ice. In the course of a feasibility study performed in December 1972, the basic operating parameters and limitations of the tool when operated on ice were determined. Following the feasibility study, operational surveys were performed totalling approximately 11 crew-months and covering in excess of 1,500 km of survey route at several locations in the Canadian Arctic. This technique is known as Electromagnetic Subsurface Profiling (ESP), and it can be considered the electromagnetic equivalent of the single-trace acoustic profiling methods used for marine sub-bottom profiling.

Campbell, W.J., **Beaufort Sea ice zones as delineated by microwave imagery**, *Journal of Geophysical Research*, Vol. 81, No. 6, 20 February 1976, pp. 1103-1110, refs.

During April 1972, microwave and IR data were obtained from the NASA CV-990 research aircraft over the Beaufort Sea ice, from the shoreline of Harrison Bay northward to a latitude of almost 81"N. The data acquired aboard the aircraft were compared with microwave data obtained on the surface at the test site of the Arctic Ice Dynamic Joint Experiment at an approximate position of 75"N, 150"W. Over this N-S transect of the polar ice canopy, it was discovered that the sea ice could be divided into five distinct zones. The shorefast sea ice was found to consist uniformly of first-year sea ice. The second zone was a mixture of first-year sea ice, medium-size multiyear floes, and many recently refrozen leads, polynyas, and open water; considerable shearing activity was evident in this zone. The third zone, in which aircraft and surface data were compared, was a mixture of first-year and multiyear sea ice that had a uniform microwave signature because the multiyear ice floes were smaller than the instantaneous field of view of the airborne microwave radiometer. The fourth zone was a mixture of first-year sea ice and medium-to-large size multiyear floes, which was similar in composition to the second zone. The fifth zone was almost exclusively multiyear ice extending to the North Pole. Zones 3, 4, and 5 are also clearly distinguishable in microwave images obtained from the Nimbus-5 satellite.

Campbell, W.J., Gloersen, P., Ramseier, R.O., and Weeks, W.F., **Integrated approach to the remote sensing of floating ice**, *International Astronautical Congress (26th)*, Lisbon, 21-27 September 1975, Proceedings, Napolitano, L.G. (ed.), Oxford: Pergamon Press, 1977, pp. 445-487, refs.

The current increase of scientific interest in all forms of floating ice--sea ice, lake ice, river ice, ice shelves, and icebergs--has occurred during a time of rapid evolution of both remote-sensing platforms and sensors. The application of these new research tools to ice studies in the Arctic and Antarctic has generally been both piecemeal and sporadic, partly because the community of ice scientists has not kept up with the rapid advances in remote sensing technology and partly because they have not made their needs known to the space community. This paper seeks to help remedy the latter shortcoming. The remote sensing requirements for floating ice studies are given, and the capabilities of various existing and future sensors and sensor combinations in meetng these requirements are discussed. The desirable future sensors are also discussed from both the research and operational points of view.

Campbell, W.J., Sellmann, P., and Weeks, W.F., **Use of side-looking airborne radar to determine lake depth on the Alaskan North Slope**, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Report No. CRREL-SR-230, May 1975, 14 pp.

Side-looking airborne radar (SLAR) imagery obtained in April-May 1974 from the North Slope of Alaska between Barrow and Harrison Bay indicates that tundra lakes can be separated into two classes based on the strength of the radar returns. Correlations between the areal patterns of the returns, limited ground observations of lake depths, and information obtained from ERTS imagery strongly suggest that freshwater lakes giving weak returns are frozen completely to the bottom while lakes giving strong returns are not. Brackish lakes also give weak returns even when they are not completely frozen. This is presumably the result of the brine present in the lower portion of the ice cover limiting the penetration of the x-band

radiation into the ice. Although the physical cause of the differences in radar backscatter has not been identified, several possibilities are discussed. The ability to rapidly and easily separate the tundra lakes into these two classes via SLAR should be useful in a wide variety of different problems.

Claassen, J.P., Erickson, R.L., Fong, R.K.T., Hanson, B.C., and Moore, R.K., **Radar systems for a polar mission, Volume 3, appendices A-D, S, T**, University of Kansas, Remote Sensing Laboratory, Lawrence, Kansas, Report No. NASA-CR-156641 and RSL-TR-291-2-V-3, June 1976, 143 pp.

Success is reported in the radar monitoring of such features of sea ice as concentration, floe size, leads and other water openings, drift, topographic features such as pressure ridges and hummocks, fractures, and a qualitative indication of age and thickness. Scatterometer measurements made north of Alaska show a good correlation with a scattering coefficient with apparent thickness as deduced from ice type analysis of stereo aerial photography. Indications are that frequencies from 9 GHz upward seeom to be better for sea ice radar purposes than the information gathered at 0.4 GHz by a scatterometer. Some information indicates that 1 GHz is useful, but not as useful as higher frequencies. Either form of like-polarization can be used and it appears that cross-polarization may be more useful for thickness measurement. Resolution requirements have not been fully established, but most of the systems in use have had poorer resolution than 20 meters. The radar return from sea ice is found to be much different than that from lake ice. Methods to decrease side lobe levels of the Fresnel zone-plate processor and to decrease the memory requirements of a synthetic radar processor are discussed.

Cooper, D.W., Heighway, J.E., Jirberg, R.J., Shook, D.F., and Vickers, R.S., **Remote profiling of lake ice thickness using a short pulse radar system aboard a C-47 aircraft**, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, Report No. NASA-TM-X-71588, 1974, 4 pp.

Design and operation of short pulse radar systems for use in ice thickness measurement are described. Two ice profiling systems were tested, an S system, which used either random noise or continuous wave modulation at 2.8 GHz, and a less powerful C band system, which operated at 6.0 GHz and did not have random noise modulation. Flight altitudes of 4,000 feet were used, but the S band system was usable at 7,000 feet allowing flights in poor weather conditions. A minimum ice thickness of four inches is required for measurement, while the thickest ice measured was 36 inches. System accuracy is plus or minus one inch.

Davis, W.D., **Environmental monitoring by remote sensing from air and space**, United States National Aeronautics and Space Administration, Washington, D.C., Report No. SP-283, 1972, pp. 107-118.

The extent of environmental monitoring by NOAA is summarized; and some of the accomplishments in environmental monitoring, that have been achieved by using data acquired by remote sensing from air and space, together with data from other sources, are reviewed. These include the detection of tropical storms; the prediction of weather with the aid of computer-prepared mosaics of the Northern Hemisphere, showing the distribution of clouds for the entire region; the measurement of vertical atmospheric temperature; global sea-surface temperature measurement; and the determination of snow and ice distribution. Satellite remote-sensing observations provide a means of relatively reliable interpolation between surface climatic reference stations making accurate observations for the purpose of detecting climatic change. The use of continuously observed satellite data in modelling of the Earth's atmosphere, in monitoring environmental quality, in determining the positions and motions of ocean currents in connection with studies of climatic change, etc., are discussed.

Dawe, T.A., Strong, D., and Worsfold, R.D., et al., **Ice characterization ground truth report: Hopedale, Labrador, winter 1977**, Memorial University of Newfoundland, St. John's, Centre for Cold Ocean Resources Engineering, field data report #6, 1 February 1978, 175 pp., refs.

Project SAR'77 was carried out to examine the merits of using a synthetic aperture radar (SAR) system for the study of sea ice forms occurring in the Labrador Sea area and on the east coast of Newfoundland. Radar flights were conducted over Hopedale on the east coast of Labrador. Ground truth information was collected prior to and during these flights. Data was acquired on the physical properties of first year shorefast sea ice and snow cover adjacent to Hopedale. The measurements and observations are presented. A selection of the SLAR imagery collected in the area is also presented and briefly discussed.

Dean, A.M., Jr., **Remote sensing of accumulated frazil and brash ice in the St. Lawrence River**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, NTIS #ADA-039 905, April 1977, 19 pp., 7 refs.

A broadbanded impulse radar system was used for aerial detection of accumulated frazil and brash ice in a 9.5-km reach of the St. Lawrence River near Ogden Island. The remote sensing and data reduction system developed for the project provided data sufficient for production of a contour map having 1-ft intervals. With this contour map, the accumulation pattern of frazil and brash ice could be analyzed. Recommenda-

tions are given for improving the performance of the aerial profiling system.

DeRycke, R.J. and Strong, A.E., **Some preliminary results of 1971 aircraft microwave measurements of ice in the Beaufort Sea**, National Environmental Satellite Service, Washington, D.C., Report No. NOAA-TM-NESS-37, June 1972, 15 pp.

Passive microwave data in the 2.8-cm (10.69 GHz) wavelength region were acquired from a NASA aircraft during the 1971 Arctic Ice Dynamics Joint Experiment (AIDJEX). Comparison of data obtained on a cloud-free day and on a day with a complete cloud cover beneath the aircraft demonstrated that the relative age of sea ice may be observed and mapped adequately by microwave sensing from satellite altitudes regardless of cloud cover.

Dunbar, M., **Interpretation of SLAR imagery of ice in Nares Strait and the Arctic Ocean**, Defence Research Establishment, Ottawa, Report No. DREO-R-712, January 1975, 42 pp.

SLAR imagery of Nares Strait was obtained on four flights carried out in January, March, and August 1973, and April 1974, by Canadian Forces Maritime Proving and Evaluation Unit in an Argus aircraft equipped with a Motorola APS-94D SLAR. The March flight also covered two lines in the Arctic Ocean, from Alert to the pole and from the pole down the 4 degrees E meridian to the ice edge at about 80 degrees N. No observations on the ground were possible, but some back-up was available on all flights from visual observations recorded in the air, and on the March flight from infrared line-scan and vertical photography.

Edgerton, A.T., Poe, G., Stogryn, A., and Williams, D.P., **A study of the microwave emission characteristics of sea ice**, Aerojet-General Corporation, El Monte, California, Microwave Division, Report No. AGC-1741R-2, July 1971, 48 pp.

A study of airborne microwave brightness temperature measurements of Arctic sea ice was conducted that consisted of (a) numerical modeling of sea ice emission, (b) identification of atmospheric effects, and (c) comparative analysis of measured results. Aircraft data were acquired by NASA/Goddard Space Flight Center, Greenbelt, Maryland, during June 1970 near Point Barrow, Alaska. Microwave measurements were performed at observational wavelengths of .51, .55, .81, .96, 1.35, 1.55, 2.81, and 3.2 cm at low (150 m) and high (9 km) altitudes. Only the low altitude data were considered in the present study since a solid cloud deck existed during most of the overflights. A major result of the present study is the general classification of sea ice brightness temperatures into categories of 'high' and 'low' emission corresponding to young and weathered sea ice, respectively.

Edgerton, A.T., Poe, G., and Stogryn, A., **A study of the microwave emission characteristics of sea ice**, Aerojet Electrosystems Co., Azusa, California, Report No. AESC-1749R-2, 15 September 1972, 144 pp.

A study is made of the applicability of presently available theories of the microwave emission properties of sea ice in explaining representative portions of the 1971 airborne passive microwave measurements taken over the Arctic ice-based AIDJEX camp. Results indicate that non-specular surface or volume (or both) scattering phenomena must be incorporated in theories of sea ice emissions before satisfactory explanations of present experimental results can be achieved. Since present theories do not include volume scattering effects, a theory of the scattering by random dielectric constant fluctuations (in a bounded medium) applicable to sea ice is derived. A theory of surface scattering for slightly rough surfaces is also derived. Interesting new theoretical results are obtained for both types of scattering. Computer programming of the volume scattering problem is partially completed and interesting new results are obtained for the one- and two-dimensional correlation functions needed in the theory of volume scattering.

Edgerton, A.T., Poe, G., Ruskey, F., Stogryn, A., and Williams, D., **Microwave emission characteristics of natural materials and the environment**, Aerojet-General Corporation, El Monte, California, Microwave Division, Report No. AGC-9016R-8, February 1971, 284 pp.

The document is the eighth and final technical report of the series. It summarizes six years of basic and applied research into the microwave emission characteristics of natural materials and the environment. Research activities encompass investigations of the ocean and coastal environment, snowpack and ice studies, sediment and soil studies, dielectric constant measurements and techniques, and analytical modeling of natural materials and the environment. Field studies were conducted with a mobile microwave laboratory containing a number of microwave radiometers and supporting instrumentation. Oceanographic research has been concerned with the effects of microwave emission of ocean surface roughness, water temperature, salinity, and surface pollutants. Hydrologic studies were concerned with the physics of microwave emission by snowpacks, and fresh and sea ice. Other investigations have been concerned with the emission characteristics of sediments and soils and the determination of soil moisture content with microwave radiometry. The report also provides a detailed account of the current year's research, which entails multiwavelength microwave radiometric measurements and numerical modeling of controlled, small-scale waves.

Edgerton, A.T., Poe, G., Sakamoto, S., Stogryn, A.,

and Trexler, D.T., **Passive microwave measurements of oceanographic phenomena, ice, and sediments,** Aerojet-General Corporation, El Monte, California, Microwave Division, Report No. AGC-9016R-7, November 1970, 112 pp.

Airborne measurements were conducted off the Northern California coast to investigate microwave emission as a function of wave conditions. The measurements were performed at observational wavelengths of 21 and 0.81 cm. A series of rosette patterns centered near the San Francisco Light Ship were flown to acquire data parallel and perpendicular to the swell line. Sea surface and meteorological conditions were monitored by the light ship. The data have been analyzed in terms of changes in the average brightness temperature due to variations in the surface roughness and direction of propagation of the swell line relative to the aircraft flight path. Power spectral density analyses have been performed to determine if periodic variations in the microwave emission can be related to the period of the predominant wave structure. Measurements were taken at various altitudes and of a variety of sea states.

Fagerlund, E. and Lundholm, G., **Sea ice-75, IR scanner results,** Research Institute of National Defence, Stockholm, Sweden, Report No. REPT-16-6, 1976, 22 pp.

During a field experiment over an ice-covered area of the Gulf of Bothnia in March 1975, several different types of remote sensing equipment were tested, including infrared thermography performed with the airborne single line scanner TEKLA in the 8 to 14 microm region. The thermal recordings were concentrated to a 5 x 5 square km test area, which was described in great detail by ground truth measurements and photography. During 14 runs at 300 to 2000 m altitude, the thermal radiation from the sea surface was recorded on photographic film and magnetic tape. The film recordings give a general survey of the apparent temperature variations within various parts of the mapped area. By processing the tape recorded information, a more detailed analysis of some interesting objects was accomplished. The results are compared with the available ground truth and aerial photographs.

Farmer, L.D. and Johnson, J.D., **Determination of sea ice drift using side-looking airborne radar,** University of Michigan, Ann Arbor, Institute of Science and Technology, Report No. 10259-1-X, 1971, 14 pp.

Side-looking airborne radar (SLAR) has been used experimentally to map sea ice conditions since the early 1960's. In conjunction with the MANHATTAN tanker test, the U.S. Coast Guard equipped a C-130 aircraft with a Philco-Ford AN/DPD-2 Side-Looking Radar (Ku band) and conducted ice mapping experiments in the Northwest Passage during September 1969. In addition to observing the overall ice conditions, individual ice floes were identified on SLAR imagery by their size, shape, and surface characteristics. The results of this experiment revealed that single ice floes, as well as general ice masses, could be tracked to an accuracy of nearly one nautical mile. Also, water currents appear to have dominant long term influence on ice drift in this area. By assuming that one can obtain measures of the wind stress, Coriolis force, and pressure gradient force, one may be able to ascertain approximate values of the surface ocean currents in the vicinity of a given floe.

Farmer, L.D. and Johnson, J.D., **Use of side-looking air-borne radar for sea ice identification,** *Journal of Geophysical Research*, Vol. 76, No. 9, 20 March 1971, pp. 2138-2155.

An experiment was conducted to assess the performance of side-looking air-borne radar (SLAR) in mapping and identifying sea ice parameters. A Philco-Ford AN/DPD-2 (Modified) SLAR was installed on a Coast Guard C-130 aircraft and flown on an experimental basis during September 1969 in conjunction with the S.S. MANHATTAN's transit of the Northwest Passage. In addition to the research effort to determine its feasibility as an ice observational technique, the SLAR was also used as a routing aid to the MANHATTAN. The results of this experiment indicate that SLAR can readily be used to detect ice concentrations, floe size and number, and water openings, and to identify through careful image interpretation, ice age, ice drift, surface topography, fractures, and pressure characteristics. SLAR's broad areal coverage, all weather, day and night capability make it an effective means of observing sea ice and for many purposes it provides observations superior to information obtained by a visual ice observer. SLAR imagery can be used in research efforts to study the formation, growth, and decay of sea ice and can be used operationally for ship routing and ice forecasting. It will be necessary to condu. similar experiments during other seasons of the year to determine whether there is a seasonal influence on the imaged appearance of sea ice.

Fleming, M.H. and Strong, A.E., **Aircraft microwave measurements of the arctic ice pack,** National Environmental Satellite Center, Washington, D.C., Report No. NESCTM-25, August 1970, 22 pp.

Microwave radiometer data (19.3 GHz or 1.6 cm) taken from an aircraft mission over the Arctic Ocean near Point Barrow, Alaska, are examined. The microwave brightness temperatures corresponding to varying ice pack conditions are correlated with simultaneous photography and infrared radiation data. Microwave measurements of the surface taken both through and from beneath a stratus cloudcover are investigated for atmospheric attenuation and emission effects. The influence of clouds is greatest when

viewing surfaces such as water, which appears cold at microwave frequencies because of its low emissivity. In general, cloudiness diminishes the capability of the 19.3-GHz radiometer to discriminate between ice and water. Polynya and other openings in the ice pack display a characteristic brightness temperature near 100°K when viewed through a cloud-free atmosphere, whereas they appear as much as 20-40°K warmer when clouds intervene between the surface and the radiometer.

Frost, R.E., Leighty, R.D., and McLerran, J.H., **Photo interpretation in the arctic and sub-arctic**, *International Conference on Permafrost*, Lafayette, Indiana, 11-15 November 1963, Proceedings, pp. 343-348, 16 refs.

Successful use by engineers of remote and often inaccessible areas is contingent on knowing the identity, physical properties, and distribution of soils and rocks and their behavior when disturbed. Regions can be studied through small-scale areal photos, assembled either in mosaic or in photo-index form. Stereoscopic pairs of contact photos typical for each major pattern are studied to determine physical characteristics of the minute features. Data are correlated and areas of agreement or disagreement are determined. In arctic and sub-arctic regions photoanalysis is significant not only because of regional remoteness and inaccessibility but also because of the problems of use, alteration, and disturbance of the frost or permafrost in the area, as well as giving the identity and distribution of the various soils and rocks.

Gloersen, P., Ramseier, R.O., Webster, W.J., and Wilheit, T.T., **Beaufort Sea ice zones by means of microwave imagery**, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, Report No. NASA-TM-X-70867, April 1975, 27 pp.

An analysis of the aircraft microwave data obtained during the AIDJEX pilot experiment is presented and compared with a recent analysis of the microwave brightness temperatures measured in situ in the vicinity of the main AIDJEX camp. The sea ice is divided into five distinct zones, the properties of each are discussed in detail.

Gloerson, P., **Microwave signatures of first-year and multiyear sea ice**, *Journal of Geophysical Research*, Vol. 78, No. 18, 20 June 1973, pp. 3564-3572.

A combination of remote sensing from an aircraft and simultaneous surface measurements have confirmed the feasibility of identifying old and new sea ice according to its emission of thermal radiation at wavelengths between 0.3 and 3 cm. Emissivity of first-year thick ice with a surface temperature of about 260 K is 0.95 or greater for wavelengths between 0.81 and 11 cm; the emissivity of multiyear ice is 0.8 at 0.81 cm and 0.95 at 11 cm, and increases monitonically in this wavelength interval. The ease with which multiyear ice can be distinguished from first-year ice by using a passive microwave radiometer is demonstrated by comparing mosaics prepared both from photographs and images of 1.55-cm radiation.

Gustajtis, K.A. and Rossiter, J.R., **Iceberg sounding by impulse radar**, *Nature*, Vol. 271, No. 5640, 5 January 1978, pp. 48-50, refs.

Estimates of the draft of irregularly shaped icebergs can be obtained from the air quickly and accurately using short-pulse radar. A small iceberg in Twillingate Harbor, Newfoundland, was sounded from a helicopter using impulse radar. The result was verified by simultaneous measurement of the iceberg's draft using side-scan sonar. The impulse radar equipment, built by the Geophysical Survey Systems, consists of a control unit and an FM tape recorder, which were mounted in a helicopter, and transmitter-receiver and antenna assembly, which was slung in a net about 6 m beneath the aircraft. The transmitted signal is a broad-band pulse with a duration of about 20 ns and a center frequency near 80 MHz. The receiver was set to accept echoes for up to 1.4 sec and by sequential sampling of the received signal, an audiofrequency replica trace was constructed and recorded on tape. After sampling, the effective repetition rate was 51.2 scans/sec. The travel time used to interpret the draft was that from the first subsurface echo that was received directly beneath the center of the iceberg. The average drift of the iceberg was estimated to be 18.0F0.9 m, with an SD of 0.7 m over 16 passes. The ht of the iceberg was also estimated, giving a draft ht ratio of 4.3:1. The chlorinity of ice samples taken near the surface of the iceberg was 1-10x10-5, indicating little contamination of the ice by seawater.

Hagman, B.B., **On the use of microwave radiation for Great Lakes ice surveillance**, United States National Oceanic and Atmospheric Administration, Environmental Research Labs., Ann Arbor, Michigan, Report No. NOAA-TM-ERL-GLERL-13, May 1976, 11 pp., refs.

With the desire to extend the Great Lakes shipping season to year-round operation comes the need for up-to-date information on ice conditions. One method investigated uses microwave (radar) remote sensing for ice surveillance. Microwave systems are advantageous because they can penetrate cloud cover, cooperate day or night, and can provide greater areal coverage at aircraft altitudes than can optical systems. For ice surveillance, radar detects a world of edges and interfaces that correspond (in gray tones) to relative amounts of backscattered radiation. Radar is effective in classifying certain ice types, conditions, and features, and for aiding ships in ice-covered waters or during severe weather. Future microwave studies should concentrate on making various radar systems operational, collecting and correlating gound

verification data with radar data, and investigating the use of satellite platforms for microwave remote sensing.

Harwood, T.A. and Poulin, A.O., **Infrared imagery in the arctic under daylight conditions**, *Symposuim on Remote Sensing of Environment (4th)*, University of Michigan, Ann Arbor, Proceedings, 12-14 April 1966, p. 231-241, 4 refs.

Infrared thermal imagery and concurrent aerial photography were obtained from various altitudes over a broad geographical area in Arctic North America and the Polar Basin prior to the start of the melt season. Solar altitudes during the periods of data collection varied from 2 to 27 degrees, and clear weather prevailed most of the time. It was found that some terrain features and conditions depicted in the infrared imagery were not apparent or were only weakly suggested in the conventional aerial photography and that solar irradiaton produced both good and bad effects in the thermal imagery. Examples of a few of these findings are presented.

Hibler, W.D., III, **Characterization of cold-regions terrain using airborne laser profilometry**, *Journal of Glaciology*, Vol. 15, No. 73, 1975, pp.329-347, 25 refs.

This paper provides a review of the characteristics of airborne laser profilometry and its application to quantitative characterization of cold-regions terrain. The limitations of profilometry due to the profiler instrumental characteristics and instability of the aircraft platform (resulting from variations in aircraft altitude and attitude) are discussed. For typical aircraft speeds of the order of 100 m/s these limitations restrict the accurately measured roughness content to the approximate wavelength range 2 m to 300 m. Digital filtering and hardware techniques for removing the aircraft motion, and hence extending the long wavelength validity of the profile, are discussed. Regarding terrain characterization, particular attention is given to Arctic sea ice. Ridge height and spacing distribution models for sea ice in conjunction with digitally processed laser profiles allow efficient characterization of sea-ice ridging using only a few parameters. In particular, a single ridging intensity parameter has been found to allow reasonable estimation of the number of ridges countered at any height level along a straight-line path. Examination of spectral characteristics of first-year and multi-year ice suggest that laser profiles may be used to identify the ice type of floes and ridges. Comparisons of laser data and submarine sonar data are made which suggest that ratios of c.6.5:1 can be used to estimate ridge keel depths from laser data. Use of laser profilometry to characterize tundra and indirectly to measure variation in snow depth is briefly discussed.

Hibler, W.D., III, **Removal of aircraft altitude variations from laser profiles of the Arctic ice pack**, *Journal of Geophysical Research*, Vol. 77, No. 36, 20 December 1972, pp. 7190-7195.

Standard, high-pass filtering procedures are not, in general, adequate for removal of aircraft altitude variation from laser profiles of the Arctic pack ice, because of the spectral overlap between the surface roughness spectrum and the aircraft height variation spectrum. Because of this overlap, a high-pass filter tends to depress high ridges and thus makes the resulting profile unsuitable for ridge height analysis. To bypass this difficulty, a straightforward, three-step process is presented. The technique consists of carrying out a conventional high-pass filtering operation and then estimating minimum points that can be used to estimate an ice-roughness base line. The estimated ice-roughness base line is then low-pass filtered. This process can be used routinely for processing various profiles, since the filter cutoffs are not critical. The filtering operations are performed by small-error, low-pass filters with guaranteed maximum errors of 0.9% outside the transition band.

Hibler, W.D., III, **Two dimensional statistical analysis of arctic sea ice ridges**, *International Conference on Sea Ice*, Reykjavik, Iceland, 10-13 May 1971, Proceedings, National Research Council, 1972, pp. 261-275, 9 refs.

From laser profile data taken over a region of sea ice with the profiles crossing in a star pattern, we have estimated the two dimensional auto-correlation function by using cubic spline techniques. From the two dimensional auto-correlation, the two dimensional power spectrum is then calculated from which the lineation and directionality of pressure ridges is determined. In particular, the two dimensional power spectrum gives the amount of variance for a given direction and frequency ridge structure. It is also possible to obtain directionality for ridges that are randomly spaced (and thus have no dominant frequency components) because this type of structure yields a two dimensional power spectrum with lineations in frequency space perpendicular to the direction of ridge structure in real space. This two dimensional technique yields a great deal more information than taking only two intersecting profiles.

Horvath, R., and Lowe, D.S., **Multispectral survey in the Alaskan arctic**, Arctic Institute of North America, Washington, D.C., Project No. NR-307-105, September 1978, 17 pp.

An aerial survey in the vicinity of Point Barrow, Alaska, during the fall of 1967 is described. Calibrated multispectral data were obtained for common Arctic features such as sea ice, thaw lakes, and polygonal soils under a variety of conditions. Quantitative and qualitative ground truth data were also acquired. Full scale analysis of these data has not yet been undertaken, but representative image examples are presented and the results of limited analysis described.

Horvath, R., **Multispectral survey of arctic regions**, University of Michigan, Ann Arbor, Institute of Science and Technology, Report No. 1248-1-L, January 1968, 29 pp.

The report describes a multispectral survey of Arctic regions conducted by the University of Michigan in the vicinity of Point Barrow during late September and early October 1967. The purpose of the effort was to obtain calibrated multispectral imagery of typical Arctic terrain and sea areas. It was envisioned that subsequent reduction and interpretation of this data would indicate the realistic potentials of multispectral remote sensing techniques as tools for scientists interested in investigating the Arctic regions of the world.

Jean, B.R., **Radar studies of arctic ice and development of a real-time arctic ice type identification system**, Texas A and M University, Remote Sensing Center, Naval Ordnance Lab., White Oak, Maryland, Report No. RSC-3005-1, 30 November 1973, 22 pp., See also NTIS #AD-A025 742 and AD-A025 739.

The Remote Sensing Center at Texas A and M University is conducting studies for the Naval Surface Weapons Center to develop a real-time, special purpose radar data processor. The purpose of this processing system is to provide ice type identification using radar scatterometer measurements. This document reports on the activities of the Remote Sensing Center during the months of September 1, 1973, through November 30, 1973, directed toward that effort.

Keck, L.J. and Young, C.W., **An air dropped sea ice penetrometer**, Sandia Labs, Albuquerque, New Mexico, Report No. SC-DR-71-0729, December 1971, 104 pp.

An air dropped penetrometer has been developed for the U.S. Coast Guard to remotely measure the thickness of sea ice. The development program is described, and the test data and results of the Arctic test program are presented and discussed. The sea ice thickness in the vicinity of Thule Air Base, Greenland, and Alert, Canada, was measured by the penetrometers with an accuracy of plus or minus 3 inches (plus or minus 7.6 cm) during the April 1971 tests.

Ketchum, R.D., Jr., and Tooma, S.G., Jr., **Analysis and interpretation of air-borne multifrequency side-looking radar sea ice imagery**, *Journal of Geophysical Research*, Vol. 78, No. 3, 20 January 1973, pp. 520-538.

During April 1968, the Naval Oceanographic Office conducted an airborne, side-looking radar experiment over the sea-ice fields north of Alaska by using the four-frequency radar system of the Naval Research Laboratory. The shorter-wavelength, X-band radar appears to have the greatest potential for sea-ice study when more definitive information is required, such as mapping, distribution of stages of ice development, and fracture pattern analysis. Pressure ridge patterns can sometimes be identified when they are present on a low-backscatter background. The L-band radar has potential value for mapping the areal distribution for surface topography. This wavelength does not receive discriminative backscatter from various ice types but seeks only the more prominent topographic features, such as ridges and hummocks. The P-band does not appear to have any characteristics that would make it valuable for sea-ice mapping. Only the most prominent features, such as large fractures and floes, were imaged by this radar.

Ketchum, R.D., Jr., **Preliminary analysis of laser terrain profiles of sea ice surfaces**, Naval Oceanographic Office, Washington, D.C., Report No. N00-IR-70-35, May 1970, 32 pp.

The paper describes the results of a preliminary analysis of laser terrain profile data obtained with coincident photography from an altitude of 1000 feet over the sea ice fields of the Beaufort Sea in April 1968. Analysis of the data reveals that sea ice surface roughness and the nature of the roughness and relative surface reflectivities, which are both manifested in the laser terrain profile, can be used to interpret the categorical stages of ice development.

Kovacs, A. and Morey, R.M., **Radar anisotropy of sea ice due to preferred azimuthal orientation of the horizontal axes of ice crystals**, *Journal of Geophysical Research*, Vol. 83, No. 12, December 1978, pp. 6037-6046.

Results of impulse radar, ice crystal c axis, and subice current measurements on the fast ice near Narwhal Island, Alaska, are presented. The crystal structure of the ice was found to have a horizontal crystal c axis with a preferred azimuthal orientation. This orientation was found to align with the direction of the current at the ice-water interface. Impulse radar reflection measurements revealed that the preferred orientation of the sea ice crystal structure behaved as a microwave polarizer. It was observed that when the antenna E field was oriented parallel with the c axis of the crystal platelets, a strong reflection of the radar signal from the bottom of the ice was obtained. However, when the antenna E field was oriented perpendicular to the c axis, no bottom reflection was detected. The results of this study fully support earlier reports of sea ice inhomogeneity and anisotropy in reference to both structure and electromagnetic energy transmission.

Krishen, K., **Remote sensing of oceans using microwave sensors**, *Remote Sensing: Energy-related Studies*, Veziroglu, T.N. (ed.), Washington, D.C.: Hemisphere Pub. Corp., 1975, pp. 61-99.

This paper presents a review of the results of a study of the ocean surface phenomena. The use of active and passive microwave sensors to detect ocean surface winds and waves, temperature, salinity, storm cells, oil slicks, and ice conditions is demonstrated. The aircraft- and spacecraft-acquired microwave data from the Naval Research Laboratory and the National Aeronautics and Space Administration/Lyndon B. Johnson Space Center are presented. The radar backscattering cross-section data show strong correlation between ocean surface winds/waves, storm regions, and oil slicks. A strong dependence upon these parameters was shown in the Ku-band at a radar frequency of 13.9 GHz. The relationships between radiometric brightness temperature and ocean surface temperature, salinity, and sea state are set forth. Altimeters and imaging radars provide measurements of geoid, sea state, underwater topography, and the progress and location of storms.

Kuhn, P.M., Ramseier, R.O., and Stearns, L.P., **Airborne infrared imagery of Arctic Sea ice thickness**, United States National Oceanic and Atmospheric Administration, Environmental Research Labs, Boulder, Colorado, Report No. NOAA TR ERL 331-APCL 34, May 1975, 19 pp., refs.

The paper presents an empirically observed correlation between ice thickness and IR brightness of ice temperature, based on heat transfer and heat flux at the sea-ice and sea-air interfaces. During the Feb.-March 1973 NASA-U.S.S.R. Bering Sea Ice Experiment (BESEX), simultaneous surface coring data were combined with IR imagery in the 840-1237 cm. SUPER-..SUPER 1 spectral band, acquired from the NASA Convair 990 Jet Laboratory. From the combined data, ice thicknesses from PLUS or MINUS .17 cm for thick ice were inferred. Coldest sea ice temperatures during BESEX, approximately -22°C to -24°C, occurred at the tops of the pressure ridges, exhibiting a singular vein-like structure clearly discernible in the highly detailed color enhanced imagery. Freshly refrozen leads and polynyas exhibited the highest brightness temperatures, averaging -3.0°C and -0.5°C, respectively.

LaGarde, V., Mock, S.J., and Tucker, W.B., **Arctic terrain characteristics data bank**, NTIS #AD-777 551, March 1974, 47 pp., 4 refs.

An arctic terrain characteristics data bank was established as part of a program to evaluate advanced surface effect vehicle (SEV) designs for arctic use. The data bank contains approximately 4300 kilometers of terrain profiles in digital form acquired with an airborne laser profilometer system, and approximately 50 digital terrain maps for areas ranging from 0.01 sq km to 1 sq km, photogrammetrically derived from aerial photography. The development and data processing techniques are described along with descriptions of the data bank contents.

Leighty, R.D., **Terrain information from high altitude side-looking radar imagery of an arctic area**, *Symposium on Remote Sensing of Environment, (4th)*, 12-14 April 1966, Proceedings, University of Michigan, Ann Arbor, 1966, pp. 575-597, 6 refs.

Radar imagery was obtained at altitudes of 30,000 to 60,000 feet over arctic terrain with an AN/APQ56 (XAA) side-looking radar (high altitude) set during two flight programs (November-December 1960 and March 1962). Generalities of terrain information retrieval from radar imagery are presented with background information on the regional terrain characteristics in northwest Greenland and discussion of representative project imagery.

McLerran, J.H., **Airborne crevasse detection**, *Symposium on Remote Sensing of Environment, (3rd)*, 14-16 October 1964, Proceedings, University of Michigan, Ann Arbor, 1965, pp. 801-802.

Experimental and theoretical work on the feasibility of aerial detection of crevasses by infrared sensing.

McLerran, J.H., **Infrared sea ice reconnaissance**, *Symposium on Remote Sensing of Environment, (3rd)*, 14-16 October 1964, Proceedings, University of Michigan, Ann Arbor, 1965, pp. 789-799, 6 refs.

Infrared sensing of sea ice has been studied over a four-year period and has shown great promise. Infrared sensing has shown some advantages over other imaging systems. It has nighttime capability and there is some relationship between thermal radiation and ice thickness. This paper presents a few illustrations of infrared imagery of sea ice with a discussion of the interpretation of each illustration. Applications and limitations are discussed briefly.

Morey, R.M., **Airborne sea ice thickness profiling using an impulse radar**, Geophysical Survey Systems, Inc., Burlington, Massachusetts, Contract #DOT-CG-81-75-1373, June 1975, 32 pp.

The remote measurement of sea ice thickness from a mobile platform has been a goal of researchers and organizations, such as the U.S. Coast Guard, for many years. Ice thickness data is needed over large areas for icebreakers operation and navigation. The objective of this contract is to evaluate a successful ground-based sea ice profiling radar when adapted to a helicopter platform. The electronic and recording equipment were mounted in a small helicopter and the radar antenna was slung on a rope 14 m below the helicopter. The thickness of fresh water ice and sea ice was successfully measured in the Canadian Arctic near Inuvik, N.W.T. Over 50 km of first year sea ice were constantly profiled. The ice thickness varied

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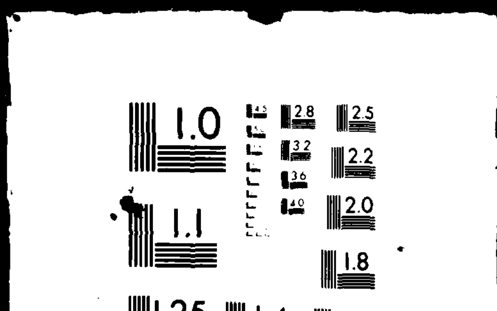

from 0.5 m to 2 m and the windswept snow cover varied from zero to 0.3 m. In the traverse mode, sea ice thickness was continuously measured at an altitude of 40 m and a speed of 65 km/hr. Theoretical considerations and experimental results are given.

Page, D.F. and Ramseier, R.O., **Application of radar techniques to ice and snow studies**, *Journal of Glaciology*, Vol. 15, No. 73, 1975, pp. 171-191, refs.

This paper presents an overview of the active microwave tools becoming available to the glaciologist with emphasis on recent radar developments as applied to floating ice. Sufficient theory is presented for the user to understand the techniques. Side-looking radar imagery is discussed using a number of examples resulting from the use of real and synthetic aperture, single and dual polarization. Recent studies of the microwave properties of ice and snow are reviewed and are shown to be leading to significant advances in high-resolution radar techniques for accurate sounding of these materials. Remote sensing of fresh water ice thickness is well established and operational, with similar techniques feasible in the near future for sea ice. It is pointed out that both imaging probing radars applied to studies of sea ice and snow usually must be used in association with data from other sensors.

Permenter, J.A., Rouse, J.W., Jr., and Schell, J.A., **Radar studies of arctic ice and development of a real-time arctic ice type identification system**, Texas A and M University, Remote Sensing Center, Report No. RSC-835-6, June 1973, 244 pp.

Studies were conducted to develop a real-time Arctic ice type identification system. Data obtained by NASA Mission 126, conducted at Point Barrow, Alaska (Site 93), in April 1970 were analyzed in detail to more clearly define the major mechanisms at work affecting the radar energy illuminating a terrain cell of sea ice. General techniques for reduction of the scatterometer data to a form suitable for application of ice type decision criteria were investigated, and the electronic circuit requirements for implementation of these techniques were determined. Also, consideration of circuit requirements are extended to include the electronics necessary for analog programming of ice type decision algorithms. After the basic circuit designs were complete, a laboratory model was constructed and a preliminary evaluation performed. Several systems modifications for improved performance are suggested.

Poulin, A.O., **Infrared aerial reconnaissance in the Arctic (spring condition)**, NTIS #AD-374 853, October 1965, 89 pp., 11 refs.

Infrared thermal imagery and concurrent conventional photography is analyzed. Imagery was obtained with a mercury-doped germanium detector in a modified AN/AAD-2 scanner, and conventional aerial phototography with Plus-X Panchromatic and infrared films was obtained with a 6-in. focal length camera. Included is sea ice of all ages; icebergs; ice islands; snow-covered terrain of various types; ice-bound and snow-covered land masses whose boundaries were visually indistinguishable; ice caps, glaciers and associated features, including crevasses and marginal lakes; and installations varying from 2-man, temporary stations to a major airbase. It was found that the thermal and visual images supplement each other to provide an effective system for aerial reconnaissance during the early Arctic spring. Infrared thermal imagery often permitted identifications of land and ice features where snow hindered visual recognition.

Strong, A.E., **Some preliminary results of 1971 aircraft microwave measurements of ice in the Beaufort Sea**, U.S. National Technical Information Service, Government Reports Announcements, Vol. 72, No. 20, 25 October 1972, p. 91.

Passive microwave data in the 2.8 cm (10.69 GHz) wavelength region were acquired from an aircraft during the 1971 Arctic Ice Dynamics Joint Experiment. Comparison of data obtained on a cloud-free day and on a day with complete cloud cover beneath the aircraft demonstrated that the relative age of sea ice may be observed and mapped adequately by microwave sensing from satellite altitudes regardless of cloud cover.

Tiuri, M., **Experiments on remote sensing of sea ice using a microwave radiometer**, Helsinki University of Technology, Otaniemi, Finland, Report No. 5-67; ISBN-951-750-329-6, 1974, 12 pp.

Investigations were carried out in Finland to determine whether microwave radiometers are useful for surveying sea ice for the purpose of guiding ice breakers in the Baltic Sea. The frequency of the radiometer was set at 4.7 GHz. The three-channel radiometer used a novel traveling wave antenna with a beam direction dependent on the frequency, and was carried by a helicopter to measure the brightness temperatures of three adjacent ice strips. An auxiliary radiometer was used at 605 MHz for checking purposes. The results of measurements made during the winter of 1974 are discussed.

U.S. Office of Naval Research, **Sea ice classification utilizing dual-frequency passive microwave techniques**, *Naval Research Reviews*, Vol. 28, No. 9, September 1975, pp. 9-23.

During December 1973, the Naval Oceanographic Office (NAVOCEANO) and the Naval Research Laboratory (NRL) conducted a joint remote sensing experiment over the sea ice fields off Scoresby Sound on the east coast of Greenland using NAVOCEANO's RP3-A BIRDSEYE aircraft, laser profiler, and infrared scanner, and NRL's 19.34 and 31.0 GHz nadir-looking radiometers. This is a two-page report summarizing the outcome of that experiment.

Zagorodnikov, A.A., **Two-dimensional statistic analysis of radar imagery of sea ice**, *International Symposium on Remote Sensing of Environment, (8th)*, University of Michigan, Ann Arbor, April 1973, pp. 279-290, refs.

Theoretical assumptions and operational techniques for obtaining morphometric characteristics of sea ice cover, using airborne remote sensing SLAR data, are discussed. The technique is based upon two-dimensional Fourier transformation of small-scale SLAR images of the ice cover by means of optical image filtering and spectral analysis of images of different areas of ice cover are given. It is shown that the optical method is apparently the most appropriate for operational statistic analysis of ice images, obtained by a side-looking airborne radar TOROS.

## C. Ground

Abele, G. and Kovacs, A., **Crevasse detection using an impulse radar system**, *Antarctic Journal of the United States*, Vol. 9, No. 4, July - August 1974, pp. 177-178.

The design and operation of an impulse radar system for use as a crevasse detector are described. The system consists of a pulse transmitter, a transmit-receive switching section, a receiver, and graphic recorder. The components are mounted inside a tracked vehicle and occupy about 1/2 cu m of space. The beam of the antenna is designed to be broadest in the forward and aft plane of the hull. The system appears to consistently detect crevasses or cracks at least 3 m ahead or to the side of the antenna and is therefore considered adequate for field party use. It is suggested, however, that the system be modified to include two antennas positioned 3 m apart and extended to distances at least 9 m in front of vehicles for better radar coverage of crevasses being approached at angles to travel routes.

Ackley, S.F. and Keliher, T.E., **Ice sheet internal radio - echo reflections and associated physical property changes with depth**, *Journal of Geophysical Research*, Vol. 84, No. 10, pp. 5675-5680.

The use of radio-echo sounding records to indicate the presence of internal layers within large ice sheets is of interest to glaciologists because it offers a possible means of tracking the internal properties of the ice sheets over large distances. In this paper we use the measured physical properties of core to bedrock taken at Cape Folger, East Antarctica (66°22'S, 111°E, 324-m depth), to compute a depth-reflection coefficient profile for comparison with the observed radio-echo reflections. The measurements available on physical properties are density variations, bubble size and shape changes, and crystal fabric variations. In calculations to differentiate the effects of the physical properties, it appears that density variations account for the primary contributions to the calculated dielectric property changes corresponding to the highest observed reflection coefficients. However, bubble changes alone can also account for reasonable, though lower, reflection coefficients at the depths corresponding to observed reflections. Crystal fabric variations correspond poorly with the reflection locations. The close correspondence between the depths of the bubble shape changes (which are definitely deformational features) and the depths of the density variations, and between both of these and the radio-echo layers, indicates that deformational events in the ice sheet's history are represented by the variations in physical properties and associated radio-echo records.

Axelsson, S., **Sea Ice-75, radar altimeter results**, Winter Navigation Research Board, Report No. REPT-16-7, 1976, 30 pp.

The results obtained at a field experiment with radar altimetry above sea-ice, carried out in the Gulf of Bothnia, March 1975, are presented. The results indicate that the envelope-detected noise of the altimetry output signal can be used for measurements on ice ridges and other large-scale surface roughnesses. The spectral characteristics of the signal also give some information about the surface roughness. The AGC-signal, which is a measure of the reflectivity of the ground surface, may be used to distinguish ice from water as well as snow-covered ice from non-covered ice. As the weather was mild during the whole test period further measurements should be carried out during a period of cold weather. Some modifications of the altimetry equipment are also recommended.

Diachok, O.I. and Mayer, W.C., **Scale model ultrasonic study of arctic ice**, Georgetown University, Department of Physics, Washington, D.C., Report No. TR-1, 12 September 1973, 14 pp.

Backscattering of ultrasonic signals from solid plates and solids are interpreted to yield information about the flexural modes of the plate and the sonic velocities in sea ice as well as the fractional ice content of the water-sea ice layer.

Dome, G.J., Hague, J., Hand, R.A., Pape, H., and Onstott, R.G., **Backscatter properties of sea ice with radar, arctic operations description and preliminary data summary**, University of Kansas, Lawrence, Remote Sensing Laboratory, Report No. RSL-TM-331-1, October 1977, 158 pp.

Active microwave responses of sea ice and lake ice were investigated at sites located off the North Alaskan Coast in the Arctic Ocean. The experimenters were ground-based at the Naval Arctic Research Laboratory, NARL, located outside of Barrow, Alaska, during May 1977, an early spring month in the Arctic. Microwave equipment was mounted on a portable A-frame type support system, which was transported to test sites via sled and snowmobile and assembled. Data were acquired at numerous microwave frequencies, receive-transmit polarizations, and angles of incidence for 5 sea ice and 2 lake ice types. This memo documents the experiment and the experimental procedure; and lists the raw experimental data.

Hibler, W.D., III, and LeSchack, L.A., **Power spectrum analysis of undersea and surface sea-ice profiles**, *Journal of Glaciology*, Vol. 11, No. 63, 1972, pp. 345-356, 7 refs., In English with French and German summaries.

Under-ice sonar profiles and surface laser profiles of the Arctic pack ice were analyzed by using power-spectrum techniques to extract significant spectral peaks corresponding to spatial periodicities in the ice. The analysis suggests that, for a section of ice samples

by two intersecting under-ice profiles, the ridges are not randomly oriented. Moreover, the lineation or directionality of the ridges may be approximately determined from the two intersecting profiles. The spectra from surface profiles of multi-year ice are of a much different nature, thus suggesting a technique for determining ice types from laser profiles.

Meyer, M.A., **Remote sensing of ice and snow thickness**, *Symposium on Remote Sensing of Environment (4th)*, 12-14 April 1966, Proceedings, University of Michigan, Ann Arbor, 1966, pp. 183-192, 2 refs.

A high resolution monocycle v.h.f. radar has been developed and tested over lake ice. Tests were conducted with the U.S. Army Cold Regions Research and Engineering Laboratory using a boom as the antenna support in 1965, and using a moving helicopter as a support in 1966. Ice thickness and snow thickness were readily measured by visual data reduction. Thickness measurement accuracies of the order of 1 cm are possible utilizing this technique. Results of measurements and the data taken are discussed as well as the expected results for such a measurement. The application of these measurements to the determination of dielectric constant is discussed.

Parashar, S.K., **Microwave emission from sea ice**, Helsinki University of Technology, Espoo, Finland, Radio Laboratory, Report No. REPT-S-90; ISBN-951-750-797-6, 1976, 19 pp.

The available literature on microwave emission from sea ice is reviewed. Sections are included on the formation of sea ice and its relevant characteristics, radiometry theory, and theory of emission. Some of the past radiometric measurements of sea ice are given. In addition, different methods that can be used to analyze the radiometric data are presented.

## D. Marine

Hagman, R., Nilsson, J., and Nilsson, Y., **Sea Ice - 75, FLAR, ODAR, ship's radar**, Winter Navigation Research Board, Stockholm, Sweden, Report No. REPT-16-5, 1976, 35 pp.

Results from a field test on sea ice mapping by radar carried out in the Gulf of Bothnia, March 1975, are presented. Three different types of radar were used: forward looking airborne search radar (FLAR), omnidirectional helicopterborne search radar (ODAR), and shipborne radars of the icebreaker TOR. It is shown that conventional radars can map the large scale ice structure of extensive areas in sufficient detail to assist navigation and ice forecasting. The radars of an icebreaker give short range navigational information on the ice situation with high resolution in real time. Different ways of recording radar information are discussed and some recommendations on further measurements of radar signatures of sea ice are given.

Hibler, W.D., III, LeSchack, L.A., and Morse, F.H., **Automatic processing of arctic pack ice data obtained by means of submarine sonar and other remote sensing techniques**, Development and Resources Transportation Co., Silver Spring, Maryland, Report No. D/RT-5, September 1970, 57 pp.

Automatic processing and analysis of three types of remote sensing data of arctic pack ice are described. The primary emphasis is on upward-looking sonar profiles of the underside of pack ice obtained during the winter 1960 arctic cruise of the SSN 583 SARGO. Two traverses, one in the Chukchi Sea and one in the Beaufort Sea, were studied. Segments of the profiles were analyzed by power spectrum and frequency distribution of amplitude techniques. Power spectrum analysis indicated preferred spacing of pressure ridges with apparent periods of 20-25, 35-40, and 80-100 m. Comparison of the power spectra of two profiles intersecting at a right angle showed the expected spatial period shift of significant ice ridge ensembles and so suggests a potential real-time technique for determining, from submarines cruising submerged, ice ridge orientation.

Wadhams, P., **A comparison of sonar and laser profiles along corresponding tracks in the Arctic Ocean**, presented at ICSI/AIDJEX Conference on Sea Ice Processes and Models, Seattle, 6-9 September 1977.

During a joint operation in the Arctic Ocean in October 1976 the British submarine HMS SOVEREIGN obtained a 4000 km long sonar profile of the ice underside while a Canadian Argus aircraft recorded a laser profile of the ice surface along the same track. Analysis of the first 1000 km of the joint profile has yielded:
(a) probability density functions for ice draft and elevation;
(b) spacing distributions for sails and keels of pressure ridges;
(c) keel draft and sail height distributions.
The keel spacing distributions show a shortage of keels at small spacings relative to a random model. This is ascribed to "keel shadowing," whereby the shallower of a pair of closely spaced keels is not detected by the keel-identifying criterion used in the analysis of the profile. The keel draft distributions follow the relationship proposed by Hibler et al (1972) at drafts greater than 9 m; below 9 m there is a deficit of keels, again ascribed to keel shadowing. The ridge height distributions, on the other hand, follow a relationship of form $n(h)dh = B\exp(-bh)dh$, where $n(h)$ is the number of sails per km track per m height increment, and B,b are parameters that depend on the nature of the ice cover. A tentative method for converting a sail height distribution into a keel draft distribution is suggested on the basis of data from ten corresponding track sections of 100 km.

## E. General

Anderson, D.M., Cooper, S., Gatto, L.W., McKim, H.L., and Merry, C.J., **Applications of remote sensing for Corps of Engineers programs in New England**, *International Symposium on Remote Sensing of Environment (10th)*, 6-10 October 1975, Ann Arbor, Michigan, Environmental Research Institute of Michigan, 1975, 8 pp., 8 refs.

The utility of satellite, high altitude, and low altitude aerial imagery is presently being critically evaluated by the Corps of Engineers. The most significant contribution to date has been to increase confidence limits by more accurately estimating parameters used in models. Within the last three years several new cooperative remote sensing programs addressing environmental and hyrologic problems have been implemented. The objectives of these programs were to determine the availability, type, scale, and resolution required and to show how remote sensing methods can be utilized to augment or update conventional procedures. Imagery from LANDSAT mission provided valuable information for site evaluation, definition of geologic lineations, and monitoring snow and ice accumulation and ablation. The Skylab program has defined the detail of land use mapping that can be accomplished from the S190A and S190B photography. Low altitude aircraft photography (scale 1:33,600) was used to determine the location of materials at a potential dam construction site that could allow a large cost saving for transportation of material as compared to original design estimates. In another program, the effect of inundation at six New England flood control reservoirs was investigated. The extent and severity of tree damage were mapped and analyzed statistically. These results will be used by the corps in the reservoir management program.

Anonymous, **Ice, remote sensing, optical effects**, *American Geophysical Union Transactions*, Vol. 53, No. 4, April 1972, pp. 397-400.

Research on icebergs, warm water intrusion, remote sensing of sea surface temperatures, and optical effects is presented.

Apinis, J.J. and Peake, W.H., **Passive microwave mapping of ice thickness**, Ohio State University, Electroscience Laboratory, Columbus, Report No. NASA-CR-149104; FR-3892-2, August 1976, 156 pp.

Basic calculations are presented for evaluating the feasibility of a scanning microwave radiometer system for mapping the thickness of lake ice. An analytical model for the apparent brightness temperature as a function of ice thickness has been developed, and elaborated to include such variables as galactic and atmospheric noise, aspect angle, polarization, temperature gradient in the ice, the presence of transition layers such as snow, slush, and water, increased loss due to air inclusions in the ice layer, and the presence of multiple ice thicknesses within the antenna footprint. It was found that brightness temperature measurements at six or seven frequencies in the range of 0.4 to 0.7 GHz were required to obtain unambiguous thickness estimates. A number of data processing methods were examined. The effects of antenna beamwidth, scanning rate, receiver bandwidth, noise figure, and integration time were studied.

Biggs, A.W., **Volume scattering from sea ice and glacier snow**, University of Kansas/Center for Research, Inc., Remote Sensing Lab, Lawrence, Kansas, Naval Ordnance Lab., White Oak, Maryland, Naval Oceanographic Office, Washington, D.C., Report No. CRINC-TR-137-2, July 1970, 46 pp.

This presentation considers volume scattering from Arctic sea ice and Cascade Mountain snow fields. Physical properties of sea ice and dielectric properties of glacier snow are described in terms of dielectric mixtures and the relaxation spectra of water at microwave frequencies. The VLF spectrum is included to illustrate analogous relaxation for ice. Scattering models are brine pockets in sea ice and ice spheroids in snow fields. Radar backscatter measurements of sea ice and SLAR images of snow fields are interpreted with these models. Simulation of sea ice in an acoustic tank demonstrates volume and surface scattering with good qualitative results. The dielectric relaxation phenomena in water at microwave frequencies is also interpreted as a mechanism for anomalous behavior.

Bilello, M.A., **Surface measurements of snow and ice for correlation with aircraft and satellite observations**, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Report No. CRREL-SR-127, May 1969, 15 pp.

The seasonal extent of the earth's snow and ice cover can easily be determined by aircraft and satellite reconnaissance. However, determination of the depth and physical properties of the snow cover and the thickness of ice on lakes, rivers, and along coastlines by these remote sensors is in an early stage of development. Correlation of the remote sensing data with actual surface conditions could be accomplished through use of an existing network of snow and ice stations located throughout North America. This network, comprising over 100 stations, is maintained by U.S. Army Terrestrial Sciences Center (USA TSC) in cooperation with other government agencies and accumulates the most extensive and reliable data for such correlation studies.

Blomquist, A., Pilo, C., and Thompson, T., **Sea Ice-75**, Winter Navigation Research Board, Stockholm, Sweden, Report No. REPT-16-9, 1976, 33 pp.

The results of a sea ice remote sensing experiment carried out in the Bay of Bothnia during March 1975

are reported. The experimental program is outlined and the sensors used including SLAR, FLAR, microwave, and IR sensors - are described. The various ice parameters studied such as thickness, roughness, concentration, and dynamics are also discussed.

Bogorodskii, V.V., **Radiosounding of ice**, NTIS # ADA-038 292, April 1977, 83 pp., 31 refs., For Russian original see CRREL #30-1854.

The pulse radiosounding technique was used in studying Antarctic land and sea ice, their internal structures, volumes, movements, and physical properties. Electromagnetic properties of different ice types and their measurement are discussed.

Bolsenga, S.J., **On the use of multispectral radar to define certain characteristics of Great Lakes ice**, National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Lab., Ann Arbor, Michigan, Report No. NOAA-TM-ERL-GLERL-17, July 1978, 18 pp.

Synoptic observations of Great Lakes ice cover are often severely hampered by weather conditions. It is possible to overcome these difficulties by using microwave radar. New areas of research using multispectral microwave radar are suggested. It seems probable that detailed structural characteristics of the Great Lakes ice cover can be described with an appropriately sophisticated radar system.

Brown, R.J., **Remote sensing of the ocean, Part I, Physical, chemical, and geological properties (a bibliography with abstracts)**, National Technical Information Service, Springfield, Virginia, June 1977, 237 pp.

The studies describe remote sensing methods as they are applied to ocean temperature, sea ice, marine biology, marine geology, and sound and light transmission. Techniques of measurement using radiometry, microwave spectroscopy, radar systems, infrared spectroscopy, and photography are described. These measurements are made from both aircraft and satellites. (This updated bibliography contains 232 abstracts, 36 of which are new entries to the previous edition.)

Byrd, R.C. and Sackinger, W.M., **Backscatter of millimeter waves from snow, ice, and sea ice**, University of Alaska, Institute of Arctic Environmental Engineering, Report No. IAEE-7207, 31 December 1972, 75 pp.

The factors contributing to the scattering of electromagnetic waves from snow, ice, and sea ice are discussed. Laboratory measurements of the complex permittivity of sea ice as a function of temperature and salinity are reported for the frequency range 26-40 GHz. Bistatic field measurements of backscatter are also described, and results presented for a wide variety of conditions of snow cover and ice topography. Surface topography and liquid water content are dominant contributors to backscatter.

Campbell, W.J., Gloersen, P., Ramseier, R.O., and Weeks, W.F., **Geophysical studies of floating ice by remote sensing**, *Journal of Glaciology*, Vol. 15, No. 73, 1975, pp. 305-328.

This paper presents an overview of recent remote-sensing techniques as applied to geophysical studies of floating ice. The current increase in scientific interest in floating ice has occurred during a time of rapid evolution of both remote-sensing platforms and sensors. Mesoscale and macroscale studies of floating ice are discussed under three sensor categories: visual, passive microwave, and active microwave. The specific studies that are reviewed primarily investigate ice drift and deformation, and ice type and ice roughness identification and distribution.

Campbell, W.J., Coon, M.D., and Weeks, W.F., **Remote sensing program required for the AIDJEX model**, *AIDJEX Bulletin*, No. 27, University of Washington,Seattle, November 1974, pp. 22-44.

This paper deals with the AIDJEX remote sensing program in reference to the AIDJEX model.

Claassen, J.P., Erickson, R.L., Fong, R.K.T., Komen, M.J., and Moore, R.K., **Radar systems for a polar mission, Volume I**, University of Kansas, Remote Sensing Lab, Lawrence, Report No. NASA-CR-156640 and RSL-TR-291-2-V-1, February 1977, 88 pp.

Use of radar is indicated for observation of phenomena in the polar regions. The present status of radar observation of sea ice (quasi-operational from aircraft), glaciers (little known), and icebergs (feasible but little research, and problems in discriminating icebergs from ships) is reviewed. Techniques for satellite observation are presented, with emphasis on use of a Scanning Synthetic-Aperture Radar required for frequently repeated coverage. Methods for processing SCANSAR data onboard the satellite were investigated, and some 5 methods appear feasible at the present time, although more research is needed. Use of CCD and SAW devices appears particularly promising in the achievement of low-power-consumption processors, but the rapid advancement of the digital art means that sampled-data analog processors using CCD and MOS devices must continually be compared with their digital competitors to determine which is best at the time a design decision must be made.

Clogh, D.J. and McQuillan, A.K., **Benefits of remote sensing of sea ice**, Canada Centre for Remote Sensing, Ottawa, Report No. RR-73-3 and REF-73-20, December 1973, 32 pp.

A preliminary analysis of the benefits and costs of remote sensing of sea ice in the Arctic, the Gulf of St. Lawrence, and the East Coast Offshore is presented.

Dehn, W.F. and Gow, A.J., **Islands of grounded sea ice**, *Environmental Assessment of the Alaskan Continental Shelf*, Vol. 14, Principal investigators' reports for the year ending March 1976, Environmental Research Laboratories, Boulder, Colorado, 1976, pp. 35-50.

Large areas of grounded sea ice have been reported by early arctic explorers and more recently by the U.S. Coast Guard. The ESSA, ERTS, NOAA, and DMSP satellites now provide multi-spectral imagery with sufficiently high resolution to allow detailed sequential observations to be made of the movement and spatial extent of arctic sea ice. This report discussed the location, formation, and decay of five large (> 30 sq km) islands of grounded sea ice in the southern Chukchi Sea as observed from an extended period of time using satellite imagery. Measurements of the bathymetry around one grounded sea ice feature are presented along with observations made and photos taken from the ice surface. The potential use of these sea ice islands as research stations is also discussed.

Deloor, G.P. and Morra, R.H.J., **Sea Ice-75, Ice detection by SLAR**, Swedish Meteorological and Hydrological Institute, Norkoeping, Sweden, Report No. REPT-16-3, 1976, 33 pp.

A sea ice remote sensing experiment was carried out in the Bay of Bothnia during March 1975 using, among other sensors, a real aperture x-band side-looking airborne radar (SLAR). The properties, possibilities, and limitations of SLAR are discussed in detail and an analysis is made of SLAR imagery in comparison with aerial photography.

Evans, S., Rinker, J.N., and Robin, G. de Q., **Radio ice-sounding techniques**, *Symposium on Remote Sensing of Environment (4th)*, 12-14 April 1966, Proceedings, University of Michigan, Ann Arbor, 1966, pp. 793-800, 11 refs.

During the summer of 1964 a cooperative research project team traversed some 450 miles of the Greenland Ice Cap to evaluate two VHF band radar systems for measuring ice thickness and contouring the bedrock profile at the ice/rock interface. A continuous radar trace of the bedrock was obtained for some 450 miles of traverse and through ice thicknesses of 4600 feet.

Fung, A.K., Moore, R.K., and Parashar, S.K., **Theory of wave scatter from an inhomogeneous medium with a slightly rough boundary and its application to sea ice**,. *Remote Sensing of Environment*, Vol. 7, No. 1, 1978, pp. 37-50, refs.

An analytical theory of electromagnetic wave scattering from an inhomogeneous medium with a slightly rough boundary surface is formulated. The inhomogeneity in the medium is assumed to vary continuously in the vertical direction. It is also assumed to have a small random variation in the horizontal direction. The medium is assumed to consist of two layers. Maxwell's equations are solved by using the small perturbation method together with Fourier transform technique. The resulting differential equations are solved by using WKB and variation of parameter methods. Field amplitudes in each medium are determined by taking boundary conditions into consideration. The expressions for first order polarized radar backscatter cross-section .SIGMA..SUPER O. are obtained. An attempt is made to apply the developed theory to compute sea ice scatter. The complex permittivity of sea ice, which depends upon both the temperature and salinity, varies with the depth of sea ice. There is certainly variation in the horizontal direction. Thus, the developed model may be able to give useful estimates when applied to sea ice scattering. Numerical calculations are performed for polarized radar backscatter cross section (.SIGMA.. SUPER O..SUB B..SUB V. AND .SIGMA..SUPERO.. SUB H..SUB H.) at two frequencies, 13.3 GHz and 400 MHz. The WKB method is applicable at both of these frequencies. These theoretical results are compared with the experimental results obtained from NASA Earth Resources Program mission 126. Theoretical results give the same absolute value of .SIGMA..SUPER O. and the relative variation among the six ice types as is given by the experimental results.

Hanson, K.J., **Remote sensing of the ocean**, *Remote Sensing of the Troposphere*, Derr, V.E. (ed.), Boulder, Colorado, Chapter 22, 56 pp.

Progress in remote sensing of the oceans has been slow since the satellite era began more than a decade ago. The reasons for this are numerous. However, the overriding reason is that, although satellite experiments were designed to study both meteorological and ocean variables, the atmospheric variables (such as cloudiness) were clearly distinguishable and had great utility for meteorologists. For the oceanographer, the satellite provided useful sea surface temperature measurement only over a small fraction of the world's oceans where upwelling and western boundary currents cause horizontal temperature gradients large enough to be detectable above atmospheric and measurement noise. It is little wonder the oceanographic community has been slow to respond to the potential offered by satellite platforms. In spite of the difficulty in interpreting sea surface temperature over broad oceanic areas, considerable progress has been made in the past five years. That progress is discussed in the first section of this chapter. Studies of the possibility of global measurement of other oceanic variables have continued. These studies have led to a great deal of optimism about the possibility of remote sensing of salinity,

temperature, surface roughness, foam, sea spray, sea ice covrage, and phytoplankton in the surface mixed layer of the ocean. Passive microwave and ocean color measurements may make these global measurements possible. They are discussed in the second and third sections of this chapter. A shortcoming of this chapter is that it does not include a discussion of the potential of active microwave sensing, or remote sensing of heat flux from the ocean surface. Because of the rapid development in these three areas, there is no single document that gives students a statement of present knowledge. To attempt to fill this need, this chapter gives the reader the parametric relationship between oceanic variables and the electromagnetic energy either emitted or reflected from the ocean surface. It also discusses what the major uncertainties are today. The atmosphere is not transparent to all electromagnetic energy and measurement systems, for remote sensing of the ocean must make use of windows in the absorption spectra of the active atmospheric gases (mainly H.Sub 2.0, CO.SUB 2., 0.SUB3., and 0.SUB 2.) in order to detect energy from the ocean. The principal atmospheric windows for visible, IR, and microwave radiation are listed. The boundaries of the windows are difficult to define because the transmissivity depends both upon concentration of the active absorbing gases and upon path length of the radiation through the atmosphere.

Hulse, W.C., Jean, B.R., and Schell, J.A., **Radar studies of arctic ice and development of a real-time arctic ice type identification system**, Texas A and M University, Remote Sensing Center, Report No. RSC-3005-7, January 1976, 69 pp.

The Remote Sensing Center at Texas A and M University is conducting studies for the Naval Surface Weapons Center to develop a real-time, special purpose radar data processor. The purpose of this processing system is to provide ice type identification using radar scatterometer measurements. This document provides information for the operation and maintenance of the developed processor system.

Jean, B.R. and Schell, J.A., **Radar studies of arctic ice and development of a real-time arctic ice type identification system**, Texas A and M University, Remote Sensing Center, Report No. RSC-3005-4, 31 August 1974, 24 pp.

The Remote Sensing Center at Texas A and M University is conducting studies for the Naval Ordnance Laboratory to develop a real-time, special purpose radar data processor. The purpose of this processing system is to provide ice type identification using radar scatterometer measurements. This document reports on the activities of the Remote Sensing Center, during the months of June through August 1974, directed toward that effort.

Jean, B.R., Permenter, J.A., Reisor, G.J., and Shay, M.T., **Radar studies of arctic ice and development of a real-time arctic ice type identification system**, Texas A and M University, Remote Sensing Center, Report No. RSC-3005-5, 31 January 1975, 106 pp.

The Remote Sensing Center at Texas A and M University is conducting studies for the Naval Surface Weapons Center to develop a real-time, special purpose radar data processor. The purpose of this processing system is to provide ice type identification using radar scatterometer measurements. This document reports on the activities of the Remote Sensing Center during the months of September 1, 1974 through January 31, 1975, directed toward that effort.

Jean, B.R., **Radar studies of arctic ice and development of arctic ice type identification system**, Texas A and M University, Remote Sensing Center, Report No. RSC-3005-6, 31 January 1976, 32 pp.

The Remote Sensing Center at Texas A and M University has conducted studies for the Naval Surface Weapons Center to develop a real-time, special purpose radar data processor. The purpose of this processing system is to provide ice type identification using radar scatterometer measurements. This final report documents the construction of the Real-Time Ice Classification System (RTICS) processor.

Kovacs, A. and Morey, R.M., **Radar anisotropy of sea ice due to preferred azimuthal orientation of the horizontal c-axes of ice crystals**, *AIDJEX Bulletin*, No. 38, March 1978, pp. 171-201, 32 refs.

Results of impulse radar, ice crystal c-axis, and sub-ice current measurements on the fast-ice near Narwhal Island, Alaska, are presented. The crystal structure of the ice was found to have a horizontal crystal c-axis with a preferred azimuthal orientation. This orientation was found to align with the direction of the current at the ice water interface. Impulse radar reflection measurements revealed that the preferred orientation of the sea ice crystal structure behaved as a microwave polarizer. It was observed that when the antenna E-field was oriented parallel with the c-axis of the crystal platelets a strong reflection of the radar signal from the bottom of the ice was obtained. However, when the antenna E-field was oriented perpendicular to the c-axis, no bottom reflection was detected. The results of this study fully support earlier reports of sea ice inhomogeneity and anisotropy in reference to both structure and electromagnetic energy transmission.

Krutiskin, B.A., *Ice Forecasting Techniques for the Arctic Seas*, New Delhi: Amerind Publishing Co. Pvt. Ltd., 1976, 230 pp., refs., Published for the Office of Polar Programs and the National Science Foundation, Washington, D.C.

This volume contains published papers by different authors on problems of the calculation and forecasting

of ice conditions in the Arctic seas. The subjects considered are as follows: a method for calculating the drift and thickness of ice with the aid of an electronic computer; the relationship between hydrometeorological processes such as the index of water circulation and index of local pressure fields to the 11-yr cycle of solar activity (Wolf numbers) and to nutation of the Earth's axis; the results of the use of successive 10-day correlations of sea surface temperature to predict autumn ice phenomena in Arctic seas; the development and application of a method based on analysis of space-time changes in the dates of ice formation to formulate short-term forecasts of ice formation; the role of solar variation and fluctuations of the Earth's pole in the variations of ice cover formation in the Arctic seas; the possibility of utilizing data on the inflow of Atlantic waters into the Arctic Ocean to predict thermal conditions in the Arctic seas; the existence of spatial correlation in the mean monthly temperatures in the vicinity of Franz Josef Land; and an analysis of the heat and dynamic processes determining the distribution of ice in the Arctic seas.

Naval Oceanographic Office, **A review of achievements in remote sensing for oceanography**, *Spacecraft Oceanography Project,* Annex A, Annex to NTIS #AD-823 210, 1 September 1966, 97 pp.

Contents: Sea State, Sea-Surface Temperature, Sea Ice, Currents and Water Masses (Color), Coastal Areas and Shoals, and Biological Phenomena.

Parashar, S., **Sea Ice-75, analysis of SLAR data**, Swedish Meteorological and Hydrological Institute, Norkoeping, Report No. REPT-16-4, 1976, 56 pp.

Results obtained from an analysis of SLAR data collected during a sea ice remote sensing experiment in the Bay of Bothnia during March 1975 are presented. The data gathered included SLAR images of sea ice obtained by utilizing EMI x-band real-aperture radar. The formation of sea ice and its relevant characteristics and the nature of radar returns from sea ice are included for background. A brief historical note on the use of radar for mapping ice is also given.

Poulin, A.O, **On the thermal nature and sensing of snow-covered arctic terrain**, Army Engineer Topographic Labs, Fort Belvoir, Virginia, Report No. ETL-RN-73-4, May 1973, 188 pp.

Thermal infrared imagery (8 to 14 micrometers) of selected areas of the North American Arctic above the 75th parallel was obtained at three different periods: early winter, midwinter, and early spring. Data runs totaling approximately 2500 nautical miles in length were made at altitudes ranging from 1000 to 20,000 feet. Environmental conditions included: (1) daytime with solar altitudes from 2 to 27 degrees and the atmosphere ranging from very clear to very hazy, and (2) very clear to very hazy conditions during the dark season. Subjects covered included sea ice, coastal areas, inland areas, lakes, streams, glaciers, the Greenland Ice Cap, and the Ward-Hunt Ice Shelf. Questions arising from analysis of the imagery led to a winter experiment in which study was concentrated on the temperature differences that develop at shorelines, but a number of secondary studies were also conducted. Aerial radiometric data and photographs were correlated with ground data, which included subsurface temperatures in the soil, ice, and snow on both sides of a shoreline. A classification system for thermal features exhibited by arctic terrain and preliminary criteria for seasonal maps was developed.

Rango, A., **Remote sensing of snow and ice: a review of the research in the United States, 1975-1978**, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, Report No. NASA-TM-79713, February 1979, 35 pp.

Research work in the United States from 1975-1978 in the field of remote sensing of snow and ice is reviewed. Topics covered include snowcover mapping, snowmelt runoff forecasting, demonstration projects, snow water equivalent and free water content determination, glaciers, river and lake ice, and sea ice. A bibliography of 200 references is included.

Rouse, J.W., Jr., **Arctic ice type identification by radar**, University of Kansas/Center for Research, Lawrence, Report No. CRES-TR-121-1, August 1968, 35 pp., Prepared in cooperation with the Arctic Institute of North America, Washington, D.C.

The pack ice in the Arctic Ocean was the subject of a special remote sensing mission conducted jointly by the National Aeronautics and Space Administration, Navy Oceanographic Office, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), the Arctic Institute of North America, and the University of Kansas. One of the most significant results of the experiment was verification of the ability, under these conditions, of a 2.25 cm wavelength radar scatterometer to identify ice types. This article presents the results of the radar experiment, and analyzes the data to determine the characteristics of radar backscatter from various Arctic ice types.

Shahrokhi, F. (ed.), *Remote Sensing of Earth Resources,* Vol. 3, University of Tennessee, Tullahoma, Space Institute, 1974, 813 pp., refs.

The papers in this volume deal with applications of remote sensing technology to specific tasks and refinements of the remote sensing techniques and more reliable detection of specific terrestrial features and improved resolution in remote sensing imagery. The applications include the following: agricultural surveys in the U.S. and India, mapping of pine tree infestation by beetles and defoliation by the gypsy moth, determination of the boundaries and movement of forest fires in the U.S., water quality surveys and ice

layer growth and movements in Lake Superior, determination of pollutant flow from sewage plants, land use conflicts and design of transportation arteries in and around metropolitan areas, etc. The papers concerned with refinements in technique discuss airborne radiometric measurements of land and sea surface temperatures, digital processing of microwave radiometric images, automatic classification methods applied to spectral photography, inherent limitations of monocular techniques for determining smoke plume parameters from aerial photography, use of remote sensing to study the dispersion of stack plumes, space photography for revision of topical maps of the world physico-geographic atlas, atmospheric correction of remotely sensed data, etc.

Sherman, J.W., III and Zaitzeff, J.B., **Oceanographic applications of remote sensing**, Naval Oceanographic Office, Washington, D.C., 1968, 31 pp.

The vastness of the oceans, the large-scale nature of many oceanic phenomena, and the slowness and expense of in-situ measurements point to a need for more rapid and continuous observations of the ocean. Ocean phenomena amenable to remote sensing from air and spacecraft include sea surface temperatures, wave conditions, water/ice/land interfaces, biological indices, and water color analyses. A tentative selection of remote sensors showing promise for oceanographic measurements is presented. Active (radar and laser) and passive sensors from the visible, infrared, and microwave regions of the spectrum are included.

Sherman, J.W., III, **Remote sensing oceanography**, Naval Oceanographic Office, Spacecraft Oceanography Project, National Aeronautics and Space Administration, Washington, D.C., Report No. SP-283, 1972, pp. 91-105.

The potential applications of electromagnetic sensors to studies of the oceans are discussed. The objectives of remote sensing programs in the developing space techniques for collecting ocean data include 1) identification, testing, and evaluation techniques that can be used on Earth survey spacecraft to provide useful oceanographic data; 2) establishing the reliability of spacecraft oceanographic data in comparison with remotely-sensed surface data, and relating the data to surface and subsurface phenomena; 3) developing and testing techniques of displaying space-acquired data on a global basis consistent with conventional synoptic data, and 4) developing forecasting techniques for dynamic ocean phenomena by using space-acquired data. The roughness features of the ocean and the penetration of electromagnetic energy into water are summarized. The application of remote sensors is reviewed in the assessment of the fishery environment, in measuring sea-surface temperature, in measuring ice movement and surveying ice conditions, in studying ocean color so as to determine the chlorophyll content of ocean waters, in shoal and coastal mapping, in studying coastal marine processes, and in synoptic oceanography.

Thoren, R., **Remote sensing as an aid for navigation in ice-covered sea areas**, Forsvarets Forskningsanstalt FOA, Stockholm, Sweden, Report No. FOA-A-30018-H3, M6, June 1978, 54 pp.

Photographic interpretations of ice are presented. How remote sensing makes under-ice navigation possible is discussed. The application of electronic reconnaissance to photointerpretation of ice is included. A comprehensive remote sensing experiment on sea ice, performed in the Bay of Bothnia, is described.

Udin, I., **Sea Ice-75, ground truth report**, Swedish Meteorological and Hydrological Institute, Norkoeping, Report No. REPT-16-2, 1976, 77 pp.

A remote sensing project over sea ice in the Bay of Bothnia was carried out during March 1975. Several sensors - microwave, visual, and infrared were tested. Following background information of ice conditions and weather, general ice parameters are presented. Satellite information and air photos are analyzed. At the same time as the remote sensing experiment, an extensive ground truth program was carried out. Various ice parameters within three different ground truth areas, one inside the other, were studied. These small scale ice observations and measurements and the ground truth program in general are discussed.

Zhmurko, V.Y., **A study of ice dynamics in the Gulf of Tartary by radio-physical methods**, Defence Scientific Information Service, Ottawa, Report No. T-526-R, July 1969, Translation of Arkticheskii i Antarkticheskii Nauchno-Issledovatel-skii Institut, *Trudy*(USSR), Vol. 284, 1968, pp. 70-75, by M. Dunbar.

In order to provide year-round navigation in the Gulf of Tartary, a thorough study of the dynamics of pack ice is necessary, as well as measurements of its physical characteristics. The observation program was designed to acquire data for the calculation of the relationships and coefficients necessary for operational information on current ice conditions and for developing ice forecasting methods.

# 4. Pressure Ridges and Leads

Ackley, S.F., and Hibler, W.D., III, **Height variation along sea ice pressure ridges and the probability of finding "holes" for vehicle crossings**, NTIS #AD-772 696, December 1973, 9 pp., 6 refs.

Height variations along sea ice pressure ridges were studied to determine whether low spots in the ridges persisted over long enough distances for a wide vehicle, such as the surface effect vehicle, to pass through them. Heights along eight pressure ridges varying in length from 0.9 km to 2.2 km were measured at 5 m intervals using aerial photographic data obtained over the Beaufort Sea. The probabilities of finding holes at the mean heights of the ridges and 0.67 m above and below the mean heights were calculated as a function of the old widths using an autocorrelation function obtained from the height data. The curves obtained were in good agreement with passage probabilities calculated directly from the data. The results indicate that the probability of finding passage through a hole at least 0.67 m below the mean ridge height is less than 0.1 for holes greater than 10 m wide. It is concluded that a large vehicle, such as a surface effect vehicle, that cannot cross ridges at their mean heights will have to go around such ridges because low, wide holes do not appear with sufficiently high probability to make hole-searching a useful method.

Ackley, S.F., Hibler, W.D., III, Kovacs, A., and Weeks, W.F., **Structure of a multi-year pressure ridge,** *Arctic*, Vol. 26, No. 1, March 1973, pp. 22-31, 12 refs., In English with French and Russian summaries.

Three transverse profiles across a large pressure ridge located in the Beaufort Sea are presented. The ridge sail extended 4 m above sea level and the ridge keel 13 m below. The cross-sections of the ridge keel can be described as roughly semi-circular. This suggests that form drag coefficients for flow transverse to the long axis of multi-year ridges may be as high as 0.8. Examination of several salinity, temperature, and brine-volume profiles shows that much of the ice in the ridge has a very low salinity and is quite strong. All the inter-block voids that initially existed in the ridge at the time of its formation have been completely filled with ice. These observations, coupled with icebreaking experience, indicate that multi-year ridges are, indeed, significant obstacles to even the largest icebreaking ship and should be avoided if possible. A very large first-year ridge with a sail height of 12.8 m is also described. This is the largest free-floating ridge yet measured.

Anderson, V.H., **Sea ice pressure ridge study: an airphoto analysis,** *Photogrammetria*, Vol. 26, No. 5/6, December 1970, pp. 201-228, 16 refs.

Tested and proven techniques of terrain analysis using conventional aerial photography were applied to interpret the patterns associated with a sea ice environment. Ages and relative thicknesses of sea ice masses were determined from stereoscopic aerial photography. A classification scheme of sea ice pressure ridges is developed based upon their linear surface trace, their relative ages, their heights, widths and lengths, their location relative to recent ice movement, and the size of the material composing the ridges. The significance of sinuous ridges with respect to straight ridges is discussed relative to the forces involved in their formation. Estimates as to the underwater components of pressure ridges are deduced based upon elements of their surface configuration and pattern.

Arya, S.P.S., **Contribution of form drag on pressure ridges to the air stress on arctic ice,** *Journal of Geophysical Research*, Vol. 78, 1973, pp. 7092-7099.

Various methods of measuring air stress on the arctic ice surface are discussed; however, none of them could possibly take into account the form drag due to pressure ridges. An expression is derived for the form drag per unit area in terms of certain key parameters measurements. Of these parameters an estimate is made of the ratio of the form drag to the frictional stress. It depends on the geographical location in the Arctic, the season of the year, and the meteorological conditions in the atmospheric surface layer. It is found, contrary to the common assumption, that the form drag on pressure ridges may be much larger than the frictional stress on the ice surface especially under stably stratified conditions.

Budgen, G.L., **The deformation of pack ice by ridging,** *Journal of Geophysical Research*, Vol. 84, No. 4, April 1979, pp. 1793-1796.

Some ideas on modeling the deformation of pack ice by ridging are presented. A theory is proposed which, by assuming a constant shape for ridge sections and coupling the ridge frequency to the mean ridge height, provides a thickness redistribution function related to previously developed statistical ridge models.

Campbell, W.J., **Ice lead and polynya dynamics,** United States Geological Survey, Washington, D.C., Professional Paper #929, pp. 340-342.

The use of ERTS to obtain high resolution sequential imagery of the change in the thickness of the ice cover and its fracturing under the influence of the

force operating on it is discussed. While ERTS does not measure the thickness of ice directly, it can be used to distinguish between classes of ice thickness and to monitor changes within each class. The ERTS images show large floes of first-year or multi-year ice that vary in thickness from 1.5 to 3 m and that can be separated by refrozen polynyas filled with gray ice that is 20 to 40 cm thick. Also, numerous new leads that are either open or have very thin ice are visible. The combination of the images with surface measurements can provide invaluable information needed to test prediction models for sea ice dynamics and thermodynamics.

Carlson, C.T., Maresca, J.W., Jr., and Seibel, E., **Ice ridge formation: probable control by near shore bars**, *Journal of Great Lakes Research*, Vol. 2, No. 2, Shelburne, Ontario, December 1976, pp. 384-392, refs.

During the 1973-1974 winter season, a time-lapse photographic system was used to provide a nearly continuous record of the ice conditions along a segment of the southeastern Lake Michigan shoreline. By analyzing the photographs, a typical sequence of nearshore ice formation through breakup was identified. From the record of nearshore ice formation, a three-element mechanism was formulated for the development of the nearshore ice ridges in the vicinity of the study site. A quantitative analysis of the photographs was used to test and verify the hypothesis that the nearshore ice ridges, offshore bars, and breaker zones are coincident in location at approximately 40, 105, and 205 m from the water's edge. Observations reveal that large quantities of sediment are incorporated into the nearshore ice and that the nearshore ice ridges are grounded on the nearshore bottom near the offshore bars. The grounded nearshore ice ridges simultaneously modify the nearshore topography and protect the shoreline and bluffline from erosion by winter storms. The degree to which the nearshore is protected or modified has not yet been established.

Coon, M.D. and Parmerter, R.R., **Mechanical models of ridging in the Arctic sea ice cover**, *AIDJEX Bulletin*, No. 19, Seattle, Washington, March 1973, pp. 59-112.

A kinematic model of pressure ridge formation is developed, in which the lateral and vertical motion of ice blocks is combined with a force balance and breaking stress calculation. A computer program encompassing several physical processes is used to simulate ridge formation in ice with thickness from 20 cm to 2 m. The resulting profiles are compared with measured profiles of other authors. The computer profiles reproduce many of the observed features. Experience with the computer model suggests additional simplifications that yield analytical models of such aspects as force displacement relations, maximum height of ridges, and the location of cracks in the ice sheet. Significant dimensionless parameters are identified, and parametric studies are presented of the functional relationships between these parameters. The maximum height, crack location, and required force are found as functions of the mechanical and geometrical properties of the ice sheet. The problem of a ridge forming from ice in a frozen lead is studied, and estimates are made of the width of lead required to cause breaking in the parent ice sheet. Typically, a force increase of two orders of magnitude is required to make the transition from building a ridge from frozen lead ice to building it from the parent ice sheet. The large forces are toward the upper end of the range of forces available, in agreement with the observation that most ridges are built from thin ice blocks. When large forces are available and the parent ice is fractured, ridges of limited height, but unlimited lateral extent, can occur. These correspond to the rubble fields that are observed occasionally. The proposed models agree with present observational knowledge and provide predictions that can be tested by future field experiments.

Coon, M.D. and Parmerter, R.R., **Model of pressure ridge formation in sea ice**, *Journal of Geophysical Research*, Vol. 77, No. 33, 20 November 1972, pp. 6565-6575.

A kinematic model of pressure ridge formation is presented, in which the lateral and vertical motion of ice blocks is combined with a force balance and breaking stress calculation. A computer program encompassing several physical processes has been used to simulate ridge formation in ice with thicknesses from 20 cm to 2 m. The resulting profiles are compared with measured profiles of other authors. A lower bound to the force required to form ridges is calculated from an energy balance and found to be of the order of the forces that may result from wind loading on the ice. When the ridge model proceeds through many steps, a limit cycle is established that provides a limiting height for ridges. This height depends on the thickness and strength of the ice. Limiting height calculations are made for ice sheets from 20 cm to 4 m thick.

Diachok, O.I., **A proposed geometrical/statistical model of sea ice ridges**, *American Geophysical Union Transactions*, Vol. 56, No. 6, June 1975, p. 383.

The determination of average sea ice ridge parameters, which are required for a theoretical model of low-frequency under-ice acoustic reflectivity from ridged sea ice, is dependent upon geometrical and statistical models of sea ice ridges (Diachok, Proc, 8th Int. Cong. on Acoustics, 1974). The following sea ice parameters are required: "effective" ridge shape, average ridge depth and width, and the number of ridges per km. A geometrical model is proposed in which the average ridge keel is represented by an infinitely long elliptical half-cylinder. The model is a modified form of the Makarov, and Wittmann-Schule

models, is in isostatic equilibrium, and appears to be a reasonable idealization of field measurements reported by Kovaks and by Francois. A statistical model is proposed in which ridge height/depth measurements obey the Rayleigh distribution function, which was shown to be in closer agreement with measurements of ridge height distributions (Tucker and Westhall,*AIDJEX Bulletin*,No. 21, 1973, p. 171), than the Gaussian distribution function proposed by Hibler et al. By fitting the Rayleigh distribution function to laser measurements of ridge sail heights, and sonar measurements of ridge keel depths, the following parameters were computed: the number of ridges per km, the average ridge depths relative to the ice-water interface, and the average ridge heights relative to the ice-air interface. The spatial variability of the computed number of ridges per km in the Arctic Ocean was found to be in good agreement with airborne visual observations of the ridge frequency reported by Wittmann and Schule. The average keel depth to sail height ratio for a set of near-coincident sail height and keel depth measurements (Kozo and Diachok,*AIDJEX Bulletin*,No. 19, 1973, p. 113) was found to be approximately 4.0, which is in fairly good agreement with on-site field measurements of ridge contours (Kovaks, Proc. Int. Conf. Sea Ice, 1972).

Foster, T.D., **Haline convection in polynyas and leads**, *Journal of Physical Oceanography*, Vol. 2, No. 4, October 1972, pp. 462-469.

A theoretical analysis of haline convection induced by the freezing of sea water is made for turbulent ocean. The nonlinear equations for two-dimensional flow are solved using the mean field approximation and expanding the variables in Fourier series. It is found that, when the depth of the mixed layer is sufficiently large, the convective process is independent of depth. Expressions for the horizontal spacing of convection cells, maximum vertical velocity, and time required for manifest convection to develop are derived for a range of Schmidt numbers appropriate for the ocean. The analysis is applied to conditions that may be typical of freshly frozen polynyas or leads in the Weddell Sea, and it is concluded that haline convection is probably an effective process as a precursor to Antarctic bottomwater formation.

Frank, M.D., Tucker, W.B., III, and Weeks, W.F., **Sea ice ridging over the Alaskan Continental Shelf**,*Journal of Geophysical Research*,Vol. 84, No. 8, August 1979, pp. 4885-4897.

Sea ice ridging statistics obtained from a series of laser surface roughness profiles are examined. Each set of profiles consists of six 200-km long flight tracks oriented approximately perpendicular to the coastline of the Chukchi and Beaufort seas. The landward ends of the profiles were located at Point Lay, Wainwright, Barrow, Lonely, Cross Island, and Barter Island. The flights were made in February, April, August, and December 1976, and one additional profile was obtained north of Cross Island during March 1978. It was found that although there was a systematic variation in mean ridge height (h) with season, with the highest values occurring in late winter, there was no systematic spatial variation in h at a given time. The number of ridges/km also were high during the late winter with the highest values occurring in the Barter Island and Cross Island profiles. In most profiles, the ice 20-60 km from the coast is more highly deformed (higher values) than the ice either nearer the coast or farther seaward. The Wadhams model for the distribution of ridge heights gives better agreement with observed values in the higher ridge categories than does the Hibler model. Estimates of the spatial recurrence frequency of large pressure ridges are made by using the Wadhams model and also by using an extreme value approach. In the latter, the distribution of the largest ridges per 20 km of laser track was found to be essentially normal.

Hanson, A. and Rigby, R.A., **Evolution of a large arctic pressure ridge**, *AIDJEX Bulletin*, No. 34, pp. 43-71.

Extensive mass balance and structural observations were carried out on a large (10-12 m) pressure ridge during the summer of 1975 at the AIDJEX main camp. The authors drilled a large number of holes through the ridge and, by redrilling previously drilled areas and by monitoring thickness gauges, were able to examine ridge development over a period of several months. Some vertical temperature profiles were taken. The mass loss from the ridge bottom proved to be several times that from the undeformed ice, apparently resulting as much from mechanical erosion as from melting. The lateral extent of the keel was substantially greater than that of the sail and the pattern of isostatic compensation of the ridge changed with time.

Hartwell, A.D., Hibler, W.D., III, and Mock, S.J., **Spatial aspects of pressure ridge statistics**, *Journal of Geophysical Research*, Vol. 77, No. 30, 20 October 1972, pp. 5945-5953, 7 refs.

The spatial aspects of sea ice pressure ridge statistics have been examined by a census of all ridges in each of three small areas in the Arctic basin. A model that predicts random orientation of ridges can be rejected at the 0.05 level of significance in each study area. Measurements of ridge spacings generally confirm the usefulness and validity of the probability density function. The estimator varies as a function of direction within the study areas, but a mean value is shown to be related to the ridge density (total length of ridges per unit area) by a simple equation.

Hibler, W.D., III, **A sea ice terrain and mobility model**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, 1974, 16 pp.

With the advent of a new generation of air cushion vehicles often called surface effects vehicles (SEVs), the nature of the Arctic pack ice as a vehicle terrain has taken on military and commercial significance. Because of this significance, studies have recently been carried out at USA CRREL in order to effectively characterize sea ice terrain for purposes of SEV mobility, as well as for other types of vehicles. These studies have involved aerial stereo photography, airborne laser profilometry, and ground measurements performed on the pack ice surface.

Hibler, W.D., III, and Mock, S.J., **Classification of sea ice ridging and surface roughness in the Arctic Basin**, NTIS #AD-787 130, 1973, pp. 244-254, 11 refs.

One- and two-parameter classification schemes for sea ice pressure ridging are reviewed. Using these classification schemes the number of ridges above any height may be predicted. 500 km of processed laser profile data flown over the arctic ice pack in November 1970 are used to illustrate the agreement between models and observation. The key parameter relates the number of ridges per kilometer above a given height encountered along a straight line path, to the ridge height distribution shape parameter, uniquely determined by the mean ridge height. Surface roughness spectral characteristics are examined and it is found that ridging intensity correlates well with surface roughness throughout the frequency range. A specific relationship between high frequency roughness (< 13 m) and ridging intensity is shown. Wind form drag values due to pressure ridges are calculated and compared to empirical wind drag values obtained by other researchers for relatively unridged ice.

Hibler, W.D., III, Mock, S.J., and Tucker, W.B., **Classification and variation of sea ice ridging in the Arctic Basin**, *AIDJEX Bulletin*, No. 23, January 1974, pp. 127-146, 16 refs.

A one-parameter model for pressure ridges is developed and compared with good agreement to more than 3000 km of laser profile data taken from November 1970 to February 1973 in the Arctic Basin. Using a parameter called ridging intensity, which may be determined for a region from the mean number of ridges per unit length and the mean ridge height, the number of ridges per kilometer at any height level may be predicted. Results from a study of regional and temporal variation in ridging indicate that although magnitudes of ridging intensity vary in time, the relative regional variations are similar. Consequently, three distinct regions of ridging intensity having relatively stable boundaries can be defined. Annual variation in new ice production due to ridging is sufficiently large to suggest that ridging plays an important role in the overall mass balance of the Arctic Basin.

Hibler, W.D., III, Mock, S.J., and Tucker, W.B., **Classification and variation of sea ice ridging in the western Arctic Basin**, *Journal of Geophysical Research*, Vol. 79, No. 18, 20 June 1974, pp. 2735-2743, 18 refs.

A one-parameter model for pressure ridges is developed and compared, with good agreement, with over 3000 km of laser profile data taken from November 1970 to February 1973 in the Arctic basin. Comparisons are also made with a previously developed two-parameter model. The number of ridges per kilometer at any height level may be well predicted from the one-parameter model by using a parameter called ridging intensity, which may be determined for a region from the mean number of ridges per unit length and the mean ridge height. Regional and temporal variations in ridging intensity in the western Arctic basin are studied. Results indicate that although magnitudes of ridging intensity vary in time, the relative regional variations are similar. Consequently, three distinct regions of ridging intensity having relatively stable boundaries can be defined. Annual variation in new ice production due to ridging is sufficiently large to suggest that ridging plays an important role in the overall mass balance of the Arctic basin.

Hibler, W.D., III, Kovacs, A., and Weeks, A.F., **Pressure ridge characteristics in the arctic coastal environment**, *International Conference on Port and Ocean Engineering under Arctic Conditions (1st)*, Proceedings, 1971, Vol. 1, pp. 152-183, 12 refs.

The Arctic ice pack is characterized by extreme irregularities in ice thickness that are produced by the motion and resulting deformation of the sea ice. Pressure ridges and hummocks, which are the largest of the ice relief features, present formidable problems to both the design of off-shore facilities and to the operation of surface and subsurface shipping. The mechanics of ridge and hummock formation are reviewed and it is shown that several distinct types of ice deformation features occur depending upon whether the formation mechanism is marginal crushing, overthrusting, or shearing. Between 1969 and the present, a number of both free-floating and grounded ridges have been examined by the authors in the Bering, Chukchi, and Beaufort Seas. Profiles of the upper and lower surfaces of the ridges were determined by leveling and by drilling and sonar, respectively, and the internal structure of the ridges was investigated by coring. Ice temperatures, salinities, and densities were obtained and brine volumes were computed from the temperatures and salinities. Representative profiles are presented. Current data bearing on the general distribution of deformation features in time and space over the Arctic Ocean are also summarized.

Hibler, W.D., III and Mock, S.J., **Ridging intensity variations in the Arctic basin**, *American Geophys-*

*ical Union Transactions*, Vol. 53, No. 11, November 1972, p. 1008.

This article pertains to sea ice, ice pressure, ice conditions, pressure ridges, and ice cover thickness.

Hibler, W.D. III, Mock, S.L., and Weeks, W.F., **Statistical aspects of sea ice ridge distribution,** *Journal of Geophysical Research*, Vol. 77, No.30, 20 October 1972, pp. 5954-5970, 13 *refs*.

A theoretical distribution function for pressure-ridge sail heights and keel depths is derived from fundamental assumptions about the randomness of the ridges. It is shown that the distribution function for ridge spacings (distance between ridges) can also be predicted from the assumption of spatially random occurrence. The suggested distribution functions are, in form, negative exponentials of the ridge height (or depth) squared and the ridge spacing, respectively. Extremely good fits were achieved to extensive data collected from sonar profiles of the lower surface. Using these models, it is possible to completely characterize the ridging,in a one-dimensional sense, by two parameters: (N), the mean number of ridges per unit length, and (h), the mean ridge height (or depth). In addition, there is a linear correlation between (N) and (h). This suggests that maps showing the distribution of (N) or (h) over an ocean covered with pack ice can be used to statistically characterize both the spacing and the height distribution of the ridges.

Hibler, W.D., III, **Statistical variations in arctic sea ice ridging and deformation rates**, *Ice Tech Symposium*, 9-11 April 1975, Montreal, Canada, Proceedings, New York, Society of Naval Architects and Marine Engineers, pp. J1-J16, 13 refs.

Past studies of statistics of pressure ridges have supplied useful information on the nature of pressure ridge height and spacing distributions as well as information on geographical and temporal variations in ridging. These statistics should be of some aid in the construction of Arctic offshore structures and in ice-breaking and shipping operations. By coupling these height and spacing statistics with information on ridge lengths, the amount of detouring necessary to avoid ridges may be estimated. Closely associated with ridging are drift and deformation studies. Two aspects of these studies applicable to this conference are (1) the prediction of the rate of opening and closing of the pack ice, and (2) estimation of typical geophysical stresses in the ice pack. Theoretical and experimental work at CRREL indicates that certain approximate rules may be invoked to estimate the divergence rate far from coastal boundaries, namely that in winter the pack ice should diverge in reasonably well localized high pressure systems, whereas in summer the ice typically diverges in low pressure systems. As regards estimates of geophysical stresses, estimates from a variety of sources suggest that maximum stresses integrated through the pack ice thickness are of the order of 10,000 to 100,000 N/n. The upper limit is approximately equal to the force required to crush 0.25-meter-thick sea ice.

Hnatiuk, J., Kovacs, A., and Wright, B.D., **Sea ice pressure ridges in the Beaufort Sea**, *IAHR Symposium on Ice Problems*, 7-9 August 1978, Lulea, Sweden, Proceedings, Part 1, International Association for Hydraulic Research, 1978, pp. 249-271, 10 refs.

The ice cover in the Beaufort Sea is characterized by extreme irregularities in thickness that are produced by the motion and resulting deformation of the sea ice. Pressure ridges, which are an integral part of this irregular and formidable ice cover, are recognized as the largest and most hazardous ice formations. Here, a number of cross-section profiles of first and multi-year pressure ridges in the Beaufort Sea are presented, which include both free-floating and grounded ice forms. The cross-sections of these multi-year ridges suggest that they can be adequately described by one ridge model with a constant sail-to-keel ratio and geometry. It is shown that the ice comprising multi-year ridges is solid, with the interblock voids existing at the time of their formation being completely filled with ice. Several first-year pressure ridge profiles are also discussed, which indicate that these ridges cannot be represented by any one geometric model as their sail to keel ratios and geometries are quite variable.

Hnatiuk, J., Kovacs, A., and Mellor, M., **Study of several pressure ridges and ice islands in the Canadian Beaufort Sea**, *Journal of Glaciology*, Vol. 20, No. 84, 1978, pp. 519-532, refs., English, French, and German summaries.

Environmental conditions in the southern Beaufort Sea are described with emphasis on pressure ridges and ice islands. Techniques for determining geometric configurations and physical and mechanical properties of sea ice structures and ice islands are described. Profiles of pressure ridges were determined by surface surveys, drill hole probes, and side-looking sonar scanning. Multiyear pressure ridges with thicknesses to 20 m and widths to 120 m were examined. The first-year ridge of 22-m thickness and 100-m width was studied. Results are given for several multiyear and the first-year ridges. Information obtained from dives under the ice is also given. Corresponding data are given for ground ice islands, with particular attention given to contact between the ice and sea bed. A 20-m thick ice island fragment grounded in 15 m of water was one of several investigated. Measurements of temperature, salinity, tensile strength, and compressive strength are given for ice taken from old pressure ridges, and factors influencing the interpretation of test data were discussed. The data obtained will be used in engineering design studies for offshore structures for drilling and production of hydrocarbons from

the Beaufort Sea area. Exploratory drilling in shallow water was already conducted, and offshore drilling from drill ships is scheduled to begin in the study area during the open water season of 1976.

Kovacs, A., **Grounded ice in the fast ice zone along the Beaufort Sea coast of Alaska**, NTIS #ADA-031 352, September 1976, 21 pp., 13 refs.

Four large, grounded, multi-year shear ridge formations were found in the grounded ice subzone of the fast ice zone near the Harrison Bay/Prudhoe Bay area of Alaska. A 16-m-long cross section of one of these formations was obtained by leveling and sonar measurements. These measurements revealed that the maximum ridge height was 12.6 m and that the formation was grounded in 17-18 m of water. The salinity, temperature, brine volume, and density of the ice were determined on samples obtained by coring. The physical characteristics of the formations as observed in satellite, SLAR, and aerial imagery indicate that these formations have not moved between the time of their formation in the fall of 1974 and August of 1976. Evidence of significant aeolian debris discoloring the ice is discussed.

Kovacs, A., **On pressured sea ice**, *International Conference on Sea Ice*, 10-13 May 1971, Reykjavik, Proceedings, National Research Council, Reykjavik, Iceland, pp. 276-295, 11 refs.

The formations and configurations of pressure-related sea ice structures are discussed. Cross-sectional profiles of five structures are presented and described. It has been determined that the depth of the below-water portions of the ridge appears to be 4 to 5 times the above-water height, that a single model can not be expected to represent the imperfect symmetry of all ridges, and that the slope of ridge keels was found to average 33 deg while that of the surface averaged 24 deg.

Kovacs, A., **Radar profile of a multi-year pressure ridge fragment**, *Arctic*, Vol. 31, No. 1, March 1978, pp. 59-62, 9 refs.

The usefulness of radar profiling pressure ridges of multi-year ice is described. Radar echoes provide thickness measurements of ridge keels and sails and help to define the most difficult of all Arctic obstacles. The author warns, however, that the radar technique is still in its infancy and all but excludes profiling the thickness of first-year ice pressure ridges.

Kovacs, A. and Mellor, M., **Sea ice pressure ridges and ice islands**, Creare, Inc., Hanover, New Hampshire, Report No. TN-122, August 1971, 127 pp., 60 refs.

The environmental conditions of ice-covered polar seas are described, with special emphasis on the pressure ridges and ice islands encountered in Mackenzie Bay and the Beaufort Sea. Techniques for determining the geometric configurations and the physical and mechanical properties of sea ice structures and ice islands are described. Profiles of pressure ridges were determined by surface surveys, drill hole probes, and side-looking sonar scanning; results are given for several multi-year ridges and one first-year ridges. Supplementary information obtained from divers under the ice is also given. Corresponding data are given for ice islands, with particular attention being given to contact between the ice and the sea bed. Measurement of temperature, salinity, tensile strength, and compressive strength are given for ice taken from old pressure ridges, and factors influencing the interpretation of test data are discussed. The main report closes with a brief discussion of some of the findings. The appendices give complete diving reports, and a full report on the performance of the SR.N6 Hovercraft.

Laskar, K. and Strengzke, K., **Ice thrust on shores of north German lakes and its effects**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-TL405, August 1973, 11 pp., Translation of *Natur and Volk*, Vol. 71, 1941, pp. 63-70.

Beach ridges may be formed by ice pressure as the result of temperature variations and subsequent volume changes of the ice cover, or by ice thrusting due to wind action pushing the ice against the shore. The latter type predominates in Germany. A specific minimum basin area is a prerequisite for large-scale thrust action. Several cases of ice thrust on the Ploner Lake (Germany) are described. The ice blocks pile up parallel over each other along the shore and push inland.

Lowry, R.T. and Wadhams, P., **On the statistical distribution of pressure ridges in sea ice**, *Journal of Geophysical Research*, Vol. 84, No. 5, May 1979, pp. 2487-2494.

Probability distributions for the heights and spacings of sea ice pressure ridges are described and compared with data from airborne laser profiles and submarine sonar profiles. The distributions are based on the variational calculations of Hibler et al. (1972) but take into account the effects of finite slope angles of ridges and of the criterion used to identify an independent ridge during computer reduction of data. The modified distributions are shown to give a much better fit for small spacings and slightly better fit for small ridge heights than the 1972 theory.

Marko, J.R., **Rectilinear leads and internal motions in the ice pack of the Western Arctic Ocean**, *Journal of Geophysical Research*, Vol. 82, No. 6, 20 February 1977, pp. 979-987, refs.

Large-scale (100-km) rectilinear lead patterns are a common feature of the Arctic Ocean ice cover. It is shown that many of the characteristics of these patterns can be explained by analogy with rock mechan-

ics. In particular, the existence of two intersecting lead sets, the typical intersection angles of 28 deg and the observed relative shearing motions are consistent with faulting associated with semibrittle failure. Further support for this explanation has been obtained by using NOAA and LANDSAT satellite imagery over an approximately 100-km-square area of the Beaufort Sea. These provide coverage of two days of ice deformation prior to the formation of a lead to 14 deg to the axis of compression. Strains of 4% over the two-day period are within the range attributed to rock distortion preceding semibrittle failure. The authors suggest that the range from brittle to plastic-type behavior is feasible within the Arctic Ocean sea ice, depending upon the applied rate of strain and/or the ambient confining pressures.

Palosuo, E., **Investigation of ice ridges in the Baltic**, Institute of Marine Research, Helsinki, Finland, See Citation No. 72-2B0573, 1969, pp. 9-14, 3 refs.

Rafting, ridging, and hummocking of ice by wind and sea current pressure are studied in the Baltic Sea. The thrust required for hummocking of ice and the thickness of the sludge mass are estimated with a simplified theoretical model. Vertical and horizontal pressure in a compressed ice belt are likewise investigated. These computations are compared to pressure observations and ice ridge thicknesses in the Baltic.

Pessl, F., Jr., **Formation of a modern ice-push ridge by thermal expansion of lake ice in southeastern Connecticut**, NTIS #AD-694 373, August 1969, 13 pp., 22 refs.

A modern ice-push ridge on the northwest shore of Gardner Lake in southeastern Connecticut is 0.6-1.2 m high and 1.2-3.1 m wide. In February and March 1967, the positions of survey stakes placed on the lake ice were measured periodically. During the same period, air and ice temperature and solar radiation intensity were also recorded. Analysis of the data supports the hypothesis that thermal expansion of the lake ice rather than wind action, was the principal cause of ice push. An ice-temperature change of approximately 1°C/hr increase for 6 hr was sufficient to induce ice thrust. In a 30-day period, the average net shoreward movement of the surveyed area of the ice surface was 1.0 m. During the 1966-67 winter, approximately 14 cu m of beach material was reworked and deposited, forming a discontinuous ice-push ridge along 260 m of shoreline.

Rothrock, D.A., **The energetics of the plastic deformation of pack ice by ridging**, *Journal of Geophysical Research*, Vol. 80, 1975, pp. 4515-4519.

A large-scale area of pack ice contains ice of various thicknesses from zero to many meters. As the area deforms, thin ice is ridged into thicker ice in a way that depends on the strain rate and the instantaneous thickness distribution. By equating the plastic work to the production of gravitational potential energy and the frictional dissipation in this ridging process we relate the yield curve for plastic deformation of the ice pack to the way ice thicknesses are redistributed by ridging.

Shapiro, L.H., **A preliminary study of ridging in landfast ice in Barrow, Alaska, using radar data**, University of Alaska, Geophysical Institute, Fairbanks, pp. 417-425, refs.

Information on movement vectors and the duration of events during ridging in the nearshore zone provides greater insight than can be gained from field study of ridges alone. Radar provides such data rather efficiently. Radar data, supplemented by field study, show that the linear aspect of a ridge may be sufficient to indicate formation in shear although the block composition of the ridge may be typical of pressure ridges, with no evidence of the intense cataclastic deformation of the ice that characterizes shear ridges. Similar observations also indicate the existence of a "limiting height" for grounded pressure ridges, which probably depends on the angle of approach of the pack ice to the ridge during growth. This, in turn, provides the basis for a hypothesis to explain the rough coincidence of the role of the landfast ice sheet with the 20-m depth contour. Plots of the variation of ice velocity with increasing distance from shore are presented for cases when hummocking and shearing were occurring at the landfast ice edge. These show a pronounced decrease in drag effects at the boundary when shearing is taking place over that during hummocking.

Wadhams, P., **Characteristics of deep pressure ridges in the Arctic Ocean**, Scott Polar Research Institute, Cambridge, England, Contract No. N00014-76-C-0660, 1978, 16 pp.

No abstract available.

# 5. Ice Conditions

Ackley, S.F., Hibler, W.D., III, Kovacs, A., Kugzruk, F.K., and Weeks, W.F., **Thickness and roughness variations of Arctic multi-year sea ice**, *AIDJEX Bulletin*, No. 25, July 1974, pp. 75-96, 31 refs.

Three lines on a multi-year ice floe in the Beaufort Sea, 200 m, 110 m, and 76 m long, were profiled by level to obtain ice surface elevation (freeboard) and snow depth, and drilled to obtain ice thickness at two meter intervals. Three models were then constructed to identify the relationship between surface elevation and ice thickness so that top roughness, bottom roughness, and thickness could be obtained from a measure of the surface elevation alone. One model used the average observed ice density of 910 kg/cu m. The second combined isostatic balance with the adjusted density. The third is basically the same as the Wittman-Markarov pressure ridge model. The first assumption overestimated the thicker ice and underestimated the thinner ice with errors in the estimate of thickness exceeding one meter. The last two models gave roughly similar results, with prediction errors of 0.40 m. The prediction accuracy is limited by the fact that the high-frequency roughness of the top ice surface (wave lengths less than 10 m) accounts for considerable variance that does not correlate with the bottom surface. An estimate is also made of the error in predicted ice thicknesses based only on the elevation of the upper ice surface as obtained by airborne laser. The error in predicted thicknesses only increased by about 10% over the error obtained from surface observations. Therefore, surface profiles obtained by an airborne laser may be a useful source of ice thickness information.

Ackley, S.F., Hibler, W.D., III, Kovacs, A., Kugzruk, F.K., and Weeks, W.F., **Thickness and roughness variations of Arctic multiyear sea ice**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-76-18, June 1976, 33 pp.

Three surface elevation and ice thickness profiles obtained during the 1972 Arctic Ice Dynamics Joint Experiment on a multiyear ice floe were analyzed to obtain relationships between surface elevation, thickness, and physical properties of the ice. It was found that for ice freeboards from 0.10 m to 1.05 m above sea level a linear relationship between ice density and freeboard could be postulated. The equation for the regression line is: Ice density = $-194f' + 974$ kg/cu m where $f'$ is the ice freeboard plus snow depth in ice equivalent at the point in question. This statistical relationship is consistent with observed physical properties, which indicate that as the ice freeboard increases, ice salinity decreases, and the higher freeboard or thicker ice therefore decreases in density. Using this variable density with freeboard relationship, a model was constructed to predict ice thickness, given ice freeboard and snow depth alone. This prediction is desirable, since snow depth and freeboard are relatively easy to obtain, whereas ice thickness can usually be obtained only by drilling through the ice. The model was compared with two other models. It was found that the variable density prediction model gave the best approximation to observed ice thickness, with a standard error between the measured and predicted value of about 0.4 m, compared with errors from 50 to 100% higher for the other two models.

Ahlnas, K. and Wendler, G., **Sea ice conditions in the Chukchi, Beaufort, East Siberian, and northern Bering Seas during March 1973, 1974, and 1975 as seen from NOAA-2, -3, and -4 satellites**, University of Alaska, Geophysical Institute, Fairbanks, pp. 83-104, refs.

A detailed analysis was made of satellite imagery, mainly from the NOAA VHRR (National Oceanic and Atmospheric Administration Very High Resolution Radiometer) in the visible and IR range, to produce maps of mean monthly ice concentration of the western Arctic Ocean for March of 1973 and 1974. As a result of the multi-daily coverage of the satellite, a total of 2552 data points divided into 47 subsections of the Arctic Ocean were analyzed. In both years, an average of 75% of usable observations was obtained, while the cloudy observations constituted 25%. The highest ice concentrations were found in the Beaufort Sea and East Siberian Sea, 85 and 81%, respectively, for March of 1973. For March of 1974, the ice concentration was, on an average, 10% higher because of a greater frequency in onshore wind components as deduced from five-day means of surface pressure differences between selected stations in the Beaufort Sea. Areas of low ice concentration were found in parts of the northern Bering Sea, along the northwest coast of Alaska, and off of Wrangle Island in both years. In 1973, low ice concentrations were observed north of the New Siberian Islands and west of Banks Island. Preferred lead directions were recorded for each subsection. The directions of ice drift appear to be connected with the winds, and the general surface water circulation centered around a large, anticyclonic gyre in the Beaufort Sea. For March of 1975, it was possible to enhance the IR band for a comparative temperature readout. For March 17 and 28, the 32-tone gray scale was expanded so that the entire white-to-black scale covered the temperature range -43 to -3°C. A 10°C temperature increase was noticed between the two dates. No temperatures near the freezing temperature of ocean water were observed. This may be due to the limitations imposed by the 1-km resolution of the satellite and atmospheric interference of fog above leads.

Aldoshin, E.I., Betin, V.V., Karakash, E.S., Kryndin, A.N., and Vladimirov, O.A., **Transactions of State Oceanographic Institute**, No. 71, Foreign Technology Division, Wright-Patterson AFB, Ohio, 4 October 1968, 216 pp., Machine translation of Gosudarstvennyi Okeanograficheskii Institut, *Trudy*(USSR), No. 71, 1964, pp. 5-140.

Seasonal and interannual variations in ice conditions and position of the edge of the ice in the far eastern seas in relation to peculiarities of atmospheric circulation; Method of precomputation of iciness of the sea of Okhotsk and Gulf of Tatary in the spring period; The possibility of forecasting the expansion of ice along western shores of the central Caspian Sea region; Iciness of the Davis strait; The periodicity of variations in iciness of the Baltic Sea; Aerial photography of ice drift in the sea.

Alvarez, J.A., **Glaciology and ice conditions in the Weddell Sea**, Servicio de Hydrografia Naval, Boletin No. 106, Argentine Republic, August 1971, 124 pp., refs., In Spanish, Reprinted in *Current Antarctic Literature*, No. 48, Washington, D.C., August 1976, p. 8, abstract only.

Ice conditions, their periodic variations, and the meteorological and oceanographic phenomena that give rise to them are investigated in the Weddell Sea. An attempt is made to predict ice formation on the basis of air temperature and other meteorological factors, but the resulting prognostications are less reliable than was hoped. Charts show temperature, pressure, and other environmental parameters.

Barnes, P., Reimnitz, E., and Toimil, L., **Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska**, *Marine Geology*, Vol. 28, No. 3-4, October 1978, pp. 179-210, refs.

LANDSAT-1 and NOAA satellite imagery for the winter 1972-1973, and various ice and seafloor data were used to study sea ice zonation and dynamics and their relation to bottom morphology and geology on the Beaufort Sea continental shelf of arctic Alaska. In early winter the location of the boundary between undeformed fast ice and westward-drifting pack ice of the Pacific Gyre is controlled by major coastal promontories. Pronounced linear pressure- and shear-ridges, as well as hummock fields, form along this boundary and are stabilized by grounding. Slippage along this boundary occurs intermittently at or seaward of the grounded ridges, forming new grounded ridges in a widening zone - the stamukhi zone. Between intermittent events along the stamukhi zone, pack-ice drift and slippage is continuous along the shelf edge, at average rates of 3-10 km/d. Slippage is restricted to a zone several hundred meters wide, and ice seaward of the slip face moves at uniform rates without discernible drag effects. A causal relationship is seen between the spatial distribution of major ice-ridge systems and offshore shoals downdrift of major coastal promontories. The shoals have apparently migrated shoreward under the influence of ice N400 m in the last 25 yr. Much of the available marine energy is expended in the stamukhi zone, whereas the inner shelf and coast, where the relatively undeformed fast ice grows, are sheltered. Anomalies in the overall arctic shelf profile seem to be related to sea-ice zonation, ice dynamics, and bottom processes. A proposed ice zonation emphasizes ice interaction with the shelf surface and differs from previous zonation. Certain aspects of the results reported here are directly applicable to planned offshore developments in the Prudhoe Bay oil field.

Bates, R.E., Bilello, M.A., and Saboe, D., **Ice condition and prediction of freeze-over on streams in the vicinity of Ft. Greely, Alaska**, NTIS #AD-681 216, October 1968, 58 pp., 15 refs.

The Delta River, within the boundary of Ft. Greely, Alaska, is mainly a series of braided channels that freeze over and can be crossed early in winter. However, ice jams and areas that remain ice free due to the influx of ground water could cause traversing problems. Descriptions of the events leading to freeze-over, including ground and aerial photos and diagrams showing the changes in river ice conditions, are given. The formation of a large ice jam on the Delta River and its probable causes are also discussed. Curves that can be used to forecast ice formation at three river locations near Ft. Greely, Alaska, were developed. Daily adjusted air temperatures, based on numerical constants are applied to the curves to provide day-to-day forecasts of the dates of freeze-over. A survey of 13 bodies of water throughout interior Alaska during 1966 showed that freeze-over occurred between 19 and 29 October.

Bates, R.E. and Bilello, M.A., **Ice thickness observations, North American Arctic and Subarctic: Pt. 1, 1958-59, 1959-60; Pt. II, 1960-61, 1961-62; Pt. III, 1962-63, 1963-64; Pt. IV, 1964-65, 1965-66**, NTIS #AD-653 143, AD-600 483, AD-649 768, AD-699 328, July 1961, February 1964, July 1966, November 1969, p. 43, p. 101, p. 103, and p. 130.

Data on ice thickness, freeze-over, breakup, ice surface conditions, etc., are given for ice stations in Canada and Alaska.

Bates, R.E., Bilello, M.A., and Riley, J., **Ice thickness observations along the coasts of eastern Canada and southern Greenland**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-SR-125, October 1970, 61 pp.

Between 1943 and 1951, the U.S. Air Force, in cooperation with Canada and Denmark, made ice thickness measurements at 22 stations along the coasts of eastern Canada and southern Greenland and on nearby lakes and rivers. This report includes the thickness data (not previously published) as well as descriptions of surface conditions, snow depths, and other information bearing on aircraft and ice sur-

face transport operations. Greatest ice thicknesses ranged from 31 inches (Presque Isle, Maine) to 94 inches (Sondre Stromfjord, Greenland). Least thicknesses at the time of maximum ice ranged from 15 inches (Presque Isle) to 47 inches (Cape Dan, Greenland). The average number of days of ice cover is given for all stations. It ranged from around 100 days in southern Newfoundland to around 250 days in northern Baffin Island.

Bates, R.E. and Bilello, M.A., **Ice thickness observations, North American Arctic and Subarctic, 1962-63, 1963-64, Pt. III**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-SR-43-Pt-3, July 1966, 105 pp.

This article pertains to supplementary detailed ice thickness observations across Alaskan rivers; Supplementary ice thickness observations and ice conditions for British Columbia, Canada; Supplementary ice thickness observations and ice conditions for Quebec and Ontario, Canada; Supplementary ice thickness observations and ice conditions for Quebec, Canada and northeastern United States.

Bates, R.E. and Bilello, M.A., **Ice thickness observations, North American Arctic and Subarctic, 1964-65, 1965-66, Pt. IV**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-SR-43-Pt-4, November 1969, 134 pp.

The report is fourth in a series of reports on lake and river ice and fast sea ice, records ice thicknesses observed throughout the North American arctic and subarctic during the 1964-65 and 1965-66 seasons. Information on ice surface conditions, dates of first ice, freeze-over and breakup, and detailed measurement of ice thickness across Alaskan rivers are also included. First reports from the Alaska National Guard on ice thickness measurements on lakes and rivers in the remote regions of interior Alaska are presented. Analyses on maximum observed ice thicknesses reported during the two winters in North America and deviations from the mean ice thickness amounts measured across Alaska rivers between 1961 and 1966 were conducted.

Bates, R.E. and Bilello, M.A., **Ice thickness observations, North American Arctic and Subarctic, 1966-67, 1967-68**, NTIS #AD-722 783, March 1971, 111 pp., 15 refs.

The paper is fifth in a series of reports on lake and river ice and land-fast sea ice, records ice thicknesses observed throughout the North American arctic and subarctic during the 1966-67 and 1967-68 seasons. Information on ice surface conditions, dates of first ice, freeze-over and breakup, and detailed measurements of ice thickness across Alaskan rivers are also included. Continued reports from the Alaska National Guard Network on ice thickness measurements on lakes and rivers in the remote regions of interior Alaska are presented. Analyses on maximum observed ice thicknesses reported during the two winters in North America and deviations from the mean ice thickness amounts measured across Alaska rivers between 1965 and 1968 were conducted.

Bates, R.E. and Bilello, M.A., **Ice thickness observations, North American Arctic and Subarctic, 1967-68, 1968-69**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-SR-43-Pt-6, June 1972, 99 pp.

This sixth in a series of reports on lake and river ice and land-fast sea ice records ice thicknesses observed throughout the North American arctic and subarctic during the 1968-69 and 1969-70 seasons. Information on ice surface conditions, dates of first ice, freeze-over and breakup, and measurements of ice thickness made on the second voyage of the S.S. MANHATTAN are also included. Continued reports from the Alaska National Guard Network on ice thickness measurements on lakes and rivers in the remote regions of interior Alaska are presented. Analyses are made of maximum observed ice thicknesses reported during the two winters in North America, including data from additional stations in western Alaska.

Bates, R.E. and Bilello, M.A., **Ice thickness observations, North American Arctic and Subarctic, 1970-71, 1971-72**, NTIS #ADA-010 329, April 1975, 103 pp., 24 refs.

This seventh in a series of reports on lake and river ice and land-fast sea ice presents ice thickness measurements observed throughout the North American arctic and subarctic during the 1970-71 and 1971-72 winter seasons. Information on surface ice conditions, dates of first ice, freeze-over and breakup, and detailed measurements of ice thickness across Alaskan rivers are also included. Some reports from the Alaska National Guard Network on ice thickness measurements in remote areas of western Alaska are also presented. Analyses were made of maximum observed ice thicknesses reported during the two winters, and deviations from the mean ice thickness measured across rivers and creeks in southeast Alaska between 1965 and 1972. A tabulation of the dates when maximum ice was observed at 25 locations in Alaska, 44 in Canada, and 1 in Greenland during each year from 1961 to 1972 is also given. Computations of the average annual date of maximum ice at all the stations and an isoline map showing the results for northern North America are presented.

Bilello, M.A. and Smith, D., **Air and water temperatures and ice conditions on the Connecticut River**, NTIS #AD-729 363, July 1971, 14 pp.

Observations made in and along the shores of the Connecticut River, near Hanover, New Hampshire, showed that the water temperature decreased from 14°C on 23 October to 3.5° on 21 November 1968. The river froze over on 10 December 1968 and the ice

water cover midriver was 9 to 11 in. thick on 16 January 1969. The water temperature beneath the ice sheet decreased from 2.3°C to 0°C just below the surface between 4 and 18 December 1968 and remained so down to a 15-ft depth until observations ended on 22 January 1969. These persistent near-freezing temperatures in the river were attributed to mixing caused by the constant flow of water beneath the ice sheet.

Bilello, M., **Ice thickness observations, North American Arctic and Subarctic, 1960-61, 1961-62**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, February 1964, 2 pp.

This report is a continuation of the current observational program and presents data on ice thickness during the 1960-61 and 1961-62 seasons. The network has been expanded to Alaska during this period and some station changes have taken place. The changes are discussed and some supplemental ice thickness data for two stations on the east coast of Greenland are presented. The data are presented in their original form in order to make them fully available to potential users. Analysis has been limited to a study of maximum ice thicknesses.

Bilello, M.A., **Surface observations of snow and ice for correlation with remotely collected data**, U.S. Department of the Air Force, Air Weather Service, Technical Report No. 196, July 1967, pp. 285-293, 12 refs.

The seasonal extension of the earth's snow and ice cover is easily determined by aircraft and satellite reconnaissance. However, determination of the depth and physical properties of snow and the thickness of ice on lakes, rivers, and along coastlines by these remote sensors is presently at an early stage of development. Correlations of the remote sensing data and actual surface conditions could well be accomplished through use of the observations being received from a network of snow and ice stations throughout North America. This network, comprising over 100 stations, is being conducted by USA CRREL in cooperation with other government agencies, including the Air Weather Service, and provides the most extensive and reliable data accumulation for such correlation studies.

Colony, R., Maykut, G.A., Rothrock, D.A., and Thorndike, A.S., **The thickness distribution of sea ice**, *Journal of Geophysical Research*, Vol. 80, No. 33, November 1975, pp. 4501-4513.

The polar oceans contain sea ice of many thicknesses ranging from open water to thick pressure ridges. Since many of the physical properties of the ice depend upon its thickness, it is natural to expect its large-scale geophysical properties to depend on the relative abundance of the various ice types. The ice pack is treated as a mixture whose constituents are determined by their thickness and whose composition is determined by the area covered by each constituent. A dimensionless function $g(h)$, the ice thickness distribution is defined such that $g(h)\,dh$ is the fraction of a given area covered by ice of thickness greater than $h$ but less than $h + dh$. A theory is developed to explain how the ice thickness distribution changes in response to thermal and mechanical forcing. The theory models the changes in thickness due to melting and freezing and the rearrangement of existing ice to form leads and pressure ridges. In its present form, the model assumes as inputs a growth rate function and the velocity field of the ice pack. The model is tested using strain data derived from the positions of three simultaneous manned drifting stations in the central Arctic during the period 1962-1964 and growth rates inferred from climatological heat flux averages. The results are compared with estimates of g based on submarine measurements of ice thickness.

Coon, M.D., Hall, R.T., and Pritchard, R.S., **Predictions of arctic ice conditions for operations**, *9th Annual Offshore Technology Conference*, 2-5 May 1977, Houston, Texas, Proceedings, Vol. 4, pp. 307-314, 25 refs.

A mathematical model is presented as an aid to forecasting of ice conditions for operations in ice-infested waters. The sea ice model interacts with the atmosphere and ocean. The importance of knowledge of ice *velocity, thickness distribution*, and stress for short-term forecasting of ice conditions is explained. A sample calculation is shown to demonstrate and clarify the results. As a test of the performance of the model, observations during the Arctic Ice Dynamics Joint Experiment (AIDJEX) and LANDSAT imagery in April 1975 are used to compare with simulated conditions, but insufficient data on barometric pressures and boundary motion affects the comparison. The model is too weak to match the observed motions as accurately as desired.

Department of the Navy, **Ice cover on the Arctic Ocean and a methodology for calculating certain ice phenomena**, Report No. Trans-2641, Washington, D.C., 9 July 1968, 196 pp., Translation of Arkticheskii i Antarkticheskii Nauchno-Issledovatelskii Institut, *Trudy*(USSR), Vol. 257, 1967, pp. 1-134.

Contents: Principles of a method for computing ice redistribution in Arctic Seas under influence of the wind during the navigation season; Results from expeditionary investigation of the drift and dynamics of the ice cover in the Arctic Basin in the spring of 1961; Effect of meteorological factors on times of ice formation; Changes in the ice content of the Laptev Sea in relation to pressure field variation in the Arctic; An approximate method for computing the time of onset of movement of icebreakers in pack ice by the impact method; Solar radiation absorption by sea ice; Accuracy in aerial observations and mapping of sea ice; Study of instability in heliogeophysical relationships.

Dirmhirn, I., **Observations on the structure of the ice cover of Neusiedler Lake**, NTIS #AD-738 156, January 1972, 5 pp., 2 refs., Translation of **Uber eie Beobachtung der Struktur der Eisdecke auf dem Neusiedler - See,** *Wetter und Leben*, Vol. 8, 1956, p. 73.

This article pertains to lake water, lake ice, light transmission, ice cover thickness, ice structure, air entrainment, and bubbles.

Doronin, Y.P., **Utilization of the numerical method of calculation for the prognosis of autumn-winter ice conditions in the Arctic Seas,** *Ice forecasting techniques for the Arctic Seas*, Gudkovic, Z.M., Krutskih, B.A., and Sokolov, A.L. (eds.), New Delhi: Amerind Publ. Co. Pvt. Ltd., 1976, pp. 87-107, refs.

A method for calculating the temperature and salinity of the water of the upper homogeneous layer for the autumn-winter period in the Arctic seas, the dates of stable ice formation, the depths of convection, the flow of heat from the water, and the thickness of the ice are described. The initial data used in the calculating scheme are as follows: 1) the temperature and salinity at the intersection point of the net on standard levels at the commencement point; 2) the thickness and composition of ice at the commencement point; and 3) the values of 10 days of temperature, wind speed, atmospheric pressure, and radiation balance from data of the polar stations. In simplifying the calculation scheme, the analytic relationship between the dates of stable ice formation and the factors determining them was obtained; namely, the temperature of the water and ice, the radiation balance, the wind speed, and the advective flow of salt. This relationship permits analysis of how a change in each of the elements can affect the date of ice formation. From Kara Sea data, it was found that during the period of cooling, the most important factors in determining the icing condition of the Arctic are the air temperature and the air movement; the index of the latter is the distribution of pressure over the sea. The results of application of the proposed method are presented, and it is shown that the method provides reasonable forecasts of the process of ice formation. A method for preparing hydrological material for calculations involving the processing of the initial data on the temperature and salinity of seawater by means of the Ural-2 computer is presented.

Fleet Weather Facility, **Eastern Arctic Sea ice analyses 1972-1975**, Report for January 1972-December 1975, Suitland, Maryland, June 1976, 214 pp.

This document presents a sequence of operational sea ice analyses prepared weekly for the Department of Defense. The analyses include the location of the ice pack edge, inner-pack ice concentrations, 7-day forecasts of the position of the ice edge, positions of major icebergs, and, occasionally, the ages and growth stages of the pack ice.

Fleet Weather Facility, **Western Arctic Sea ice analyses 1972-1975**, Report for January 1972-December 1975, Suitland, Maryland, June 1976, 212 pp.

This document presents a sequence of operational sea ice analyses prepared weekly for the Department of Defense. The analyses include the location of the ice pack edge, inner-pack ice concentrations, 7-day forecasts of the position of the ice edge, positions of major icebergs, and, occasionally, the ages and growth stages of the pack ice.

Fleet Weather Facility, **Eastern-Western Arctic Sea ice analyses,** Suitland, Maryland, 1977, 106 pp.

The principal aim of this publication is to provide operators and researchers with historical weekly hemispheric analyses of sea ice conditions derived principally from satellite imagery supplemented by conventional observations.

Gordon, A.L. and Taylor, H.W., **Seasonal change of Antarctic Sea ice cover**, *Science*, Vol. 187, 31 January 1975, pp. 346-347, Lamont-Doherty Geological Observatory, Palisades, New York, Report No. LDGO-2182, 31 January 1975, 3 pp.

This article concerns itself with a study of the seasonal change of the Antarctic Sea ice cover. The hypothesis presented is that much of the ice growth and retreat is due to processes related to the wind stress within the sea ice fields. After the data are presented and evaluated, the conclusion is that the winter expansion of the sea ice surrounding Antarctica and the subsequent retreat of the ice in summer may be linked with the wind stress acting on the Southern Ocean in conjunction with the heat exchange in open water regions within the ice fields.

Gow, A.J. and Kovacs, A., **Some characteristics of grounded floebergs near Prudhoe Bay, Alaska**, NTIS #ADA-031 844, September 1976, 10 pp., 11 refs.

Some physical characteristics of two grounded floebergs near Prudhoe Bay, Alaska, are described. Cross-sectional profiles of the sails and keels of both floebergs were obtained. Additional studies included investigations of the internal structure of the floebergs, surveys of the sea floor for evidence of scoring induced during grounding of the floebergs, and a brief examination of the organic and sedimentary debris found entrained within the floebergs.

Hutcheon, R.J., **Sea ice conditions in the Cook Inlet, Alaska, during the 1969-70 winter**, National Weather Service, Anchorage, Alaska, Report No. NOAA-TM-AR-6, September 1972, 15 pp.

A chronological description of ice formation is given and the 1969-70 ice year is compared to other years. Tables of Cumulative Degree Days at Anchorage, Alaska, are listed.

Hutcheon, R.J., **Sea ice conditions in the Cook**

**Inlet, Alaska, during the 1970-71 winter**, National Weather Service, Anchorage, Alaska, Report No. NOAA-TM-AR-7, October 1972, 23 pp.

Ice in Cook Inlet during the winter of 1970-1971 was rough and persistent. The first ice was sighted on the 17th of October, and the Inlet was not ice free in the spring until the 20th of May. The ice was at its farthest extent late in January, south to Cape Douglas on the western side of the Inlet and Anchor Point on the eastern side, with fast ice reported in Kachemak Bay extending up to 3 miles from the northern shore.

Khromtsova, M.S. and Kirillov, A.A., **Many-year variations of the ice coverage of the Greenland Sea and methods of forecasting it**, *AIDJEX Bulletin*, No. 16, Seattle, Washington, October 1972, pp. 46-55.

The ice cover of the Greenland Sea was investigated from the data for the periods 1924-1968. The many-year variations in the seasonal march of ice cover are analyzed, and the relationship between ice cover and various hydrometeorological factors (atmospheric temperature, Wolf sunspot number, number of days with E-type circulation, etc.) is subjected to correlation analysis. Empirical equations for forecasting ice cover for Aug., July, and June in the Greenland Sea, two to six months in advance, are presented. The ice cover in the Greenland Sea is subject to substantial year-to-year seasonal variations. Maximum ice coverage is mainly in March-April and is minimum in August. Ice clearing is highest in July. Seasonal ice persistence is weak. The correlation between air temperature in Barentsburg in Oct.-Feb. and ice cover in summer is high and ranges from -0.34 (May) to -0.62 (Aug.). The correlation between ice cover of the Greenland Sea and the quantity of Atlantic water reaching the northern part of the sea, and farther north through the Fram Strait into the Arctic basin, improves from spring to summer.

Lenggenhager, K., **Observations of asparagus or rod ice (Beobachtungen von Spargel-oder Stangeneis)**, *Zeitschift fur Meteorologie*, Vol. 25, No. 5, Berlin, 1975, pp. 322-324, In German.

The phenomenon of asparagus- or rod-shaped ice, which forms in stagnant lakes in Switzerland towards early summer, is described with photographs. These features form perpendicularly to the horizontal cover and gradually separate from each other; at a slight touch, they become friable. Their magnitude and thickness depend upon the thickness of the ice layer; a length of 5.25 cm was observed on cleft ice slabs on the banks of mountain lakes. Rod-shaped ice was not found in draining glacial lakes with a constant water level. An examination of this phenomenon leads to the conclusion that the formation of this rod-shaped ice is a result of lateral tension.

Naval Oceanographic Office, **BIRDS EYE 11-65, 4-18 December 1965**, Report No. 0-4-66, Washington, D.C., April 1966, 62 pp.

Project BIRDS EYE is an Arctic ice research program conducted by the U.S. Naval Oceanographic Office (NAVOCEANO). Its aims include improvement of objective ice observing techniques, development and testing of new procedures for data acquisition, instrument testing and evaluation, refinement of forecasting techniques, and continuing acquisition of statistical and historical data for present and future application to military Arctic operations. Data continuity, basic to understanding the character and behavior of Arctic ice, is provided by utilization of aerial observation platforms.

Naval Oceanographic Office (Bourn, M.F.), **BIRDS EYE 3-66, 11-27 April 1966**, Report No. NOO-IM-66-20, Washington, D.C., August 1966, 139 pp.

Data collected by ice observers during Naval Oceanographic Office polar research flights known as BIRDS EYE missions are contained in this report covering the third mission of 1966. The ice data include distribution, stages of development, topography, types of water openings, and ice boundaries. Ridge counts provide geographic distribution, number, and height of topographic features. Water opening data include the number, width, and orientation of water openings. The overall effectiveness of the mission is included as an *evaluation* table. The majority of water openings in the polar basin were covered with younger types of ice, although more open water was evident than was observed on BIRDS EYE 2-66. Ice concentrations were near ten tenths in the polar basin; lighter concentrations were observed in Alaskan coastal waters. Weather conditions were excellent. BIRDS EYE flight tracks are generally repeated over the same areas to maintain continuity. The tracks cover the Arctic Basin and penetrate all the bordering waters with the exception of the Laptev and Kara Seas. The aircraft is an EC-121-K radar-configured Super Constellation manned by the Oceanographic Air Survey Unit based at the Naval Air Station, Patuxent River, Maryland.

Naval Oceanographic Office (Bourn, M.F.), **BIRDS EYE 5-66, 12-22 July 1966**, Report No. NOO-IM-66-25, Washington, D.C., October 1966, 104 pp.

Data collected by ice observers during Naval Oceanographic Office polar research flights known as BIRDS EYE missions are contained in this report covering the fifth mission of 1966. The ice data include distribution, stages of development, topography, types of water openings, and ice boundaries. Ridge counts provide geographic distribution, number, and height of topographic features. Water opening data include the number, width, and orientation of water openings. The overall percentage of effectiveness of the mission is included as an evaluation table. BIRDS EYE 5-66

was conducted during daylight hours. Concentrations across the Arctic Basin were generally nine to ten tenths with much lighter concentrations near the Alaskan coastal areas. Stages of development within the Arctic Basin were predominantly polar ice with thick winter prevalent in the Chukchi Sea and in the Spitzbergen area. Evidence of recent pressure was rarely observed. Special ice features and arctic airport approaches were photographed for training and familiarization of new personnel. BIRDS EYE flight tracks are generally repeated over the same areas to maintain continuity. The tracks cover the Arctic Basin and penetrate all the bordering waters with the exception of the Laptev and Kara Seas. The aircraft is a specially configured Super Constellation manned by the Oceanographic Air Survey Unit based at the Naval Air Station, Patuxent River, Maryland.

Naval Oceanographic Office (Clark, D.), **BIRDS EYE 7-66, 28 September-8 October 1966**, Report No. NOO-IM-66-30, Washington, D.C., December 1966, 71 pp.

Data collected by ice observers during Naval Oceanographic Office polar research flights knows as BIRDS EYE missions are contained in this report covering the seventh mission of 1966. The ice data include distribution, stages of development, topography, types of water openings, number, and height of topographic features. Water opening data present the number, width, and orientation of water openings. The over-all effectiveness of the mission is included as an evaluation table. In comparison with BIRDS EYE 6-66, the sub-arctic areas showed considerable increase in concentrations. For example, the track from Keflavik to Thule increased in concentration two to three tenths. A slight increase in ridging over these areas was observed but was not significant because of its occurrence in the younger forms of ice. The area adjacent to the north Alaskan coast showed similar characteristics. Concentrations over the arctic basin showed a slight increase over those observed during BIRDS EYE 6-66. The number of water openings had correspondingly decreased, primarily due to refreezing with medium winter ice.

Naval Oceanographic Office (Dehn, W.S.), **BIRDS EYE 8-66, 25 October-7 November 1966**, Report No. NOO-IM-66-32, Washington, D.C., December 1966, 121 pp.

Data collected by the ice observers from the U.S. Naval Oceanographic Office on polar research flights known as BIRDS EYE missions are contained in this report covering the eighth mission of 1966 (BE 8-66). The manner in which these data were recorded is discussed. The over-all effectiveness of observations were made under daylight, twilight, and moonlight conditions. Operations were scheduled to take advantage of optimum light over the arctic basin. The over-all ice concentrations of the arctic basin were ten-tenths with vast floes predominant, and the primary age was arctic pack. Most water openings were refrozen with very little open water observed. No significant leads were recorded over the arctic basin. Many new topographic features were noted. The Chukchi Sea was mostly ice free to near 73N on the 28th of October; however, it was almost completely frozen north of Cape Lisburne on the 4th of November. Although flying conditions were generally good, some middle and high cloudiness hampered ridge counts. The effectiveness of the mission was excellent. The BIRDS EYE 8-66 mission was repeated after a period of 6 days in order to record changes in concentrations, topography, and water openings that occurred when the ice was under the influence of the same pressure systems.

Naval Oceanographic Office (Haggerty, J.J., III), **BIRDS EYE 9-66, 21 November-11 December 1966**, Report No. NOO-IM-66-33, Washington, D.C., March 1967, 103 pp.

BIRDS EYE 9-66 observations were scheduled to take advantage of optimum moonlight over the arctic basin. Overall ice concentrations in the arctic basin had reached a maximum of ten-tenths with vast floes being the predominant form and representing an increase in concentration over BIRDS EYE 8-66. Also, considerably more medium floes had been observed during the previous BIRDS EYE. An increase of concentration to ten tenths in Alaskan Coastal waters represented an increase of two to three tenths from the previous BIRDS EYE. Normal seasonal increases in ice concentrations occurred along the remaining tracks. Comparison of BIRDS EYE 9-66 data with data for a similar period of 1965 reveals that ice concentrations over the arctic basin were much the same. In east Greenland waters, ice concentrations were two to four tenths lighter than they were during the same period during 1965. The BIRDS EYE 9-66 mission included repeat tracks in the arctic basin after a period of 8 days in order to record short-period changes in ice conditions. Most water openings were refrozen with very little open water observed on the initial tracks; however, numerous new openings were observed on repeated tracks during and after the passage of a well-developed, low-pressure system. Many new topographic features were noted. Flying conditions were generally poor. Clouds obscuring the moon hampered water opening and ridge counts.

Naval Oceanographic Office (Boeger, A.C.), **BIRDS EYE 1-67, 15-28 January 1967**, Report No. NOO-IR-67-23, Washington, D.C., April 1967, 137 pp.

Data collected by ice observers from the U.S. Naval Oceanographic Office on polar research flights known as BIRDS EYE missions are contained in this report covering the first mission of 1967 (BE 1-67). The manner in which these data were recorded is discussed. The overall effectiveness of the mission is included in

an evaluation table. BIRDS EYE 1-67 observations were made under daylight, twilight, and moonlight conditions. Operations were scheduled to take advantage of optimum light over the arctic basin. Ten-tenths overall ice concentrations in the arctic basin were similar to conditions observed during the same time period last year (BIRDS EYE 1-66). Lighter concentrations were observed in Baffin Bay and along the East Greenland coast. These observations appeared to be consistent with those taken during BIRDS EYE 9-66 (21 November through 11 December), but lighter than the ice concentrations observed during BIRDS EYE 1-66. Little open water observed over the arctic basin is quite normal for this time of year. Increased ridging over the previous BIRDS EYE was observed in the vicinity of Point Barrow and was also heavier than observed during BIRDS EYE 1-66. Flying conditions were generally good but were poor east of Greenland and north of Cape Lisburne. Landing lights were used for illumination during periods when moonlight was obscured by clouds. The BIRDS EYE 1-67 mission was considered highly effective. Portions of the BIRDS EYE 1-67 mission were repeated after a period of 8 days in order to record changes in ice conditions.

Naval Oceanographic Office (Barrett, R.M.), **BIRDS EYE 6-68, 18 September-2 October 1968**, Report No. NOO-IR-69-6, Washington, D.C., February 1969, 120 pp.

BIRDS EYE 6-68 was a regularly scheduled Arctic ocean ice reconnaissance mission covering the Arctic Basin and the peripheral seas east from Greenland to 30 degrees E from 18 September to 2 October 1968. Ice observations were made mostly under daylight hours with weather conditions ranging from exceptionally good to poor. Ice conditions showed that the ice edge exceeded its normal mean position north of 71 degrees N in the Greenland Sea and in the western Barents Sea. Severe ice conditions existed east and north of Vestspitsbergen. Refreezing had begun north of 71 degrees N in the Greenland Sea. An ice chart is included to show observed conditions.

Naval Oceanographic Office (Agee, H.J.), **BIRDS EYE 8-68, 29 November-16 December 1968**, Report No. NOO-IR-69-47, Washington, D.C., May 1969, 103 pp.

BIRDS EYE 8-68 was a regularly scheduled Arctic Ocean ice reconnaissance mission covering the North American sector of the Arctic Basin, including the Greenland Sea in Denmark Strait from 29 November to 16 December 1968.

Naval Oceanographic Office (Freeman, R.F. and Jerdon, H.P.), **BIRDS EYE 4-69, 26 May-15 June 1969**, Report No. NOO-IR-69-79, Washington, D.C., October 1969, 210 pp.

BIRDS EYE 4-69 was a regularly scheduled Arctic Ocean ice reconnaissance mission covering the North American sector of the Arctic Basin, including its adjacent seas and the Parry Channel in the Canadian Archipelago from 26 May to 15 June 1969. Ice observations were made under daylight conditions. Low overcast existed during most flights, but good visibility allowed viewing of the icepack on numerous occasions. In the Greenland Sea, extensive ice coverage as observed on BIRDS EYE 3-69 (23 March-22 April) continued to exist northwest of Iceland; however conditions approached normal elsewhere. In Parry Channel, ice conditions since BIRDS EYE 1-69 (23 January-7 February) improved from Baffin Bay to Resolute with little change westward. The fast ice boundary along the north Alaskan coast as well as a recurring polynya, which had recently formed south of Banks Island, were recorded.

Naval Oceanographic Office (Freeman, R.F. and Rankin, R.D.), **BIRDS EYE 6-69, 5-17 September 1969**, Report No. NOO-IR-70-12, Washington, D.C., March 1970, 140 pp.

BIRDS EYE 6-69 was a regularly scheduled Arctic Ocean ice reconnaissance mission covering the Canadian Archipelageo, Baffin Bay, and the area west of Banks Island from 5 to 17 September 1969. Ice observations contained in this report were made under daylight conditions. Weather conditions were excellent west of Banks Island and throughout Parry Channel; conditions elsewhere varied from poor to good. Remnant ice in Baffin Bay exceded extreme conditions depicted in H.O. Publication 705 (*Oceanographic Atlas of the Polar Seas)*. Parry Channel was ice free from Baffin Bay to near Resolute; however, icebergs existed in eastern Lancaster Sound. Seven to eight oktas of heavily puddled ice existed in Viscount Melville Sound and M'Clure Strait with some refreezing. Lesser concentrations occurred within 30 nautical miles of Prince of Wales Strait. Shelf ice fragments were sighted within the pack ice. The icebreaking tanker SS MANHATTAN was located near 74 dg 36 min N, 104 deg 30 min W. Ice data from special flights made in April and May are included. Ice data obtained in the Canadian Archipelago and Polar Basin areas during April and May 1969 are also included.

Naval Oceanographic Office (Freeman, R.F. and Jerdon, H.P.), **BIRDS EYE 7-69, 21 October-5 November 1969**, Report No. NOO-IR-70-17, Washington, D.C., April 1970, 102 pp.

BIRDS EYE 7-69 was a regularly scheduled Arctic Ocean ice reconnaissance mission covering the North American sector of the Arctic Basin, including the Greenland Sea and Denmark Strait from 21 October to 5 November 1969. Ice observations were taken under daylight conditions in lower latitudes and in moonlight at higher latitudes. Three tracks were flown as planned; the remaining tracks were modified or cancelled owing to adverse weather or poor illumination. The ice edge east of Greenland was 15 to 25

nautical miles south of its normal position. Large amounts of new, nilas, and young ice lay behind the edge. New ridges were observed within the pack northwest of Alaska. Radarscope photographs of T-3 located near 85 deg 56 min N, 121 deg 51 min W are included. Russian ice station NP-17 sighted at 87 deg 30 min N, 11 deg 00 min E appeared to be abandoned.

Naval Oceanographic Office (Agee, H.J. and Freeman, R.F.), **BIRDS EYE 8-69, 17 November-3 December 1969**, Report No. NOO-IR-70-39, Washington, D.C., June 1970, 113 pp.

BIRDS EYE 8-69 was a regularly scheduled Arctic Ocean ice reconnaissance mission covering the North American sector of the Arctic Basin, including the Greenland Sea, Denmark Strait, and Baffin Bay between 17 November and 3 December 1969. Ice observations were taken under twilight or moonlight conditions except southeast of Greenland. Adverse weather and/or illumination limited ice observing in certain areas. The ice edge in the Greenland Sea and Denmark Strait was located south of its normal position. Two isolated giant floes or possible ice islands were located northwest of Alaska. Ice Island T-3 was located at 85 deg 38 min N, 120 degrees W.

Naval Oceanographic Office (Freeman, R.F. and Monroe, M.R.), **BIRDS EYE 6-70, 2-15 December 1970**, Report No. NOO-IR-71-7, Washington, D.C., October 1971, 70 pp.

BIRDS EYE 6-70 was a regularly scheduled Arctic Ocean ice reconnaissance mission over areas east and west of Greenland between 2 and 15 December 1970. Ice observations were taken under twilight or moonlight conditions. An infrared scanner operated over the site of recent volcanic activity on Jan Mayen Island.

Naval Oceanographic Office (Freeman, R.F. and Monroe, M.R.), **BIRDS EYE 2-71, 3-15 February 1971**, Report No. NOO-IR-71-9, Washington, D.C., November 1971, 126 pp.

BIRDS EYE 2-71 was a regularly scheduled Arctic Ocean ice reconnaissance mission covering areas east and west of Greenland between 3 and 15 February 1971. Ice observations were taken under daylight, twilight, or moonlight conditions. Poor weather and/or illumination restricted visibility to 4 km or less over 50 percent of the tracks.

Naval Oceanographic Office (Freeman, R.F.), **BIRDS EYE 3-71, 2-25 March 1971**, Report No. NOO-RI-71-10, Washington, D.C., November 1971, 219 pp.

BIRDS EYE 3-71 was a regularly scheduled ice reconnaissance mission covering the North American sector of the Arctic Ocean and included Denmark Strait and Greenland Sea between 2 and 25 March 1971. An airborne laser profilometer system was used to obtain ice surface profiles. An infrared scanner and aerial camera were used to assess ice conditions. Ice observations were made under daylight or twilight conditions. Data were collected at Camp 200 (Project AIDJEX) on 21 and 23 March. Coincidental USCGC EDISTO (WAGB-284) ice data collected in Denmark Strait are appended.

Naval Oceanographic Office, **Report of the Arctic Ice Observing and Forecasting Program, 1961**, Annual Report No. 10, Washington, D.C., December 1964, 2 pp.

A summary of NAVOCEANO and Danish ice operations during 1961 is presented. Operational aspects of obtaining and disseminating ice information and the ice forecasting and observing program are discussed. Ice charts depict observed synoptic ice conditions throughout the year. Locations of oceanographic stations occupied in the polar and subpolar regions are included.

Naval Oceanographic Office, **Report of the Arctic Ice Observing and Forecasting Program, 1962**, Annual Report No. 11, Washington, D.C., April 1965, 2 pp.

The eleventh annual report summarizes the ice program of the U.S. Naval Oceanographic Office. Although the program principally supports Military Sea Transportation Service supply operations in the eastern Arctic, many allied projects were also included. The ice forecasting and observing program in the North American Arctic has not only provided direct support to sealift operations but has also made possible the accumulation of historical data necessary for effective planning and successful execution of Arctic operations.

Nikolayev, S.G., **Calculation of ice cover of the Gulf of Finland for the spring navigable period**, *Meteorology and Hydrology*, No. 5, May 1975, pp. 86-91, refs.

A brief description is given of the method for precomputation of characteristics of the ice cover in the Gulf of Finland for the second half of the winter navigable periods. The method is elaborated by taking into account the thermal effect of water upon the ice masses of the near-ice-edge area, the intensity of which changes as a result of increase in the solar radiation from the sea surface, which causes recession of the ice edge towards the head of the Gulf of Finland.

Perchal, R.J. and Potocsky, G.J., **Long-range ice outlook, Antarctic (1969-70)**, Naval Oceanographic Office, Report No. NOO-SP-100(69), Washington, D.C., December 1969, 20 pp.

An outlook of sea ice conditions expected in the Ross Sea and McMurdo Sound regions of Antarctica is presented for the period mid-December 1969 through mid-February 1970. Oceanographic and climatic data

for these areas were analyzed in terms of sea ice growth during the past austral winter. These analyses, combined with ice conditions observed by aerial reconnaissance on 2 and 18 November and by satellite for the period 11 through 18 November and a comprehensive study of historical ice and climatic information, formed the basis for the 1969-70 Ice Outlook. In summary, heavy ice conditions were observed in the Ross Sea and the light conditions and a near-normal extent of fast ice were observed in McMurdo Sound on the preliminary aerial reconnaissance. Ice conditions are expected to be lighter in McMurdo Sound and heavier in the Ross Sea in comparison to the 1968-69 season.

Pustovalova, T.V., **Our knowledge of ice regime of the Kurisches Haff**, Naval Oceanographic Office, Report No. NOO-Trans-476, Washington, D.C., 1970, 13 pp., Translation of Gidrometeorologicheskaya Observatoriya, *Trudy*(USSR), No. 1, 1964, pp. 182-187, by M. Slessers.

Data gathered by observation stations since 1900 disclose the nature and variations of ice condition in the Kurisches Haff. As a rule, the ice is thicker in the wider central and southern parts of the gulf than in the narrowing northern part of gulf, which is more subjected to the influence of the sea. The mean duration of ice is 80 days, minimum 30 days, maximum 3.5-4 months. The ice usually appears at the beginning of December, the mean date being 3 December, the early date 31 October, the late date 21 January. The ice disappears in March, the mean date being 20 March, the early date 6 February, the late date 18 April.

Schell, I.I., **Large-scale sea ice, sea surface temperature anomalies in the northwestern North Pacific and their significance for foreshadowing the weather in northern Japan and Far Eastern U.S.S.R.**, *Journal of the Meteorological Society of Japan*, Vol. 50, No. 6, December 1972, pp. 542-557.

A composite and individual year analysis of the large-scale anomalies in the ice limit in the Okhotsk Sea during the Dec.-March quarter was made in relation to the contemporary and following April-June, July-Sept., Oct.-Dec. pressure distribution, storm frequency, temperature, and precipitation in northern Japan and Far Eastern U.S.S.R. The results obtained show that years with severe (light) ice conditions in the Okhotsk Sea are associated with a greater (lesser) frequency of storms, below (above) average temperatures, and lighter (heavier) precipitation in northern Japan and Far Eastern U.S.S.R. in the Dec.-March and, also, the following April-June periods, in keeping with the temporal coherence of the circulation or its persistence. The results obtained further show a complex pattern of temperature and rainfall in the July-Sept. quarter, as a reaction to the imbalance in the circulation imposed by the inertia during the preceding Dec.-June period, and a pattern of circulation, temperature, and precipitation the following Oct.-Dec. quarter, similar to that in the preceding Dec.-June period, as a reassertion of the original pattern resulting from the still unexpended inertia, and hence, of significance for foreshadowing (in limited cases) the April-June and Oct.-Dec. weather of northern Japan and Far Eastern U.S.S.R, from a consideration of the ice conditions the previous Dec.-March period. A similar analysis, based on anomalies of sea-surface temperatures off northeastern Japan, showed little relationship.

Swinzow, G.K., **Ice cover of an arctic proglacial lake**, NTIS #AD-632 987, March 1966, 43 pp., 15 refs.

This report contains the results of two field seasons of research on Lake Tuto, N.W. Greenland. Special forms of ice and coarse air inclusions called "worm bubbles" are reported. An observation of ice waste from the upper surface at low temperatures is attributed to a combination of sublimation and abrasion by blowing snow. Temperatures in the 2 m thick ice cover, as well as in water, were observed during ice growth. These and other observations suggest that sunlight is the main heat source and that sun penetration of the ice may raise the water temperatures an appreciable degree. It was found that the lake water contains 3 percent to 4 percent gas while the ice contains 0.5 percent of dissolved gases of a composition probably differing from that of the air. Free gas was found in the form of exsolutions in the ice of the lake, giving it a specific character. Existing theories of solute rejection by the moving solid-liquid interface are found inadequate for the case of the ice-water-gas system. It was concluded that worm bubbles may form by a mechanism other than nucleation at the interface.

Volkova, N.A., **Investigation of the ice conditions in the Arctic seas and methods of forecasting and computation, second half**, University of Washington, Seattle, Division of Marine Resources, Report No. AIDJEX-72-17, December 1972, 115 pp., Translated from Arkticheskii i Antarkticheskii Nauchno-Issledovatelskii Institut, *Trudy*(USSR), Vol. 303, 1971.

The document is a Russian-to-English translation (for the National Science Foundation by the Israel Program for Scientific Translations) of the last nine papers printed in *Trudy (Proceedings)* of the Arctic and Antarctic Research Institute, Vol. 303. The papers cover a wide range of topics related to ice conditions in the arctic seas, including numerical modeling and forecasting.

Weeks, W.F., **Sea ice conditions in the Arctic**, *AIDJEX Bulletin*, pp. 173-205, 24 refs., Includes as Appendix 1 a section on ice terminology.

This part of the original report describes in general

terms the types of ice found in the Arctic, the terminology used to describe them, the main factors controlling the physical property variations of the ice, and the seasonal variations in ice conditions. A more detailed discussion of ice properties and geometry is given in the article that follows this one.

Wilson, C., **Climatology of the cold regions, northern hemisphere Part I**, NTIS #AD-674 185, August 1969, 158 pp., refs., For Part I, see CRREL #24-3401.

Three major topics are treated in this paper: temperature, humidity and precipitation, and surface winds. Temperature data for structural design, vegetation and soil temperatures, and inversions are presented. Visibility and icing data are included with the section on atmospheric humidity and precipitation. Average and maximum wind speeds with their prevailing directions and blowing snow data are given.

Zakharov, V.F., **Manifestation of atmospheric cycles in ice-cover coefficient**, *AIDJEX Bulletin*, No. 16, University of Washington, Seattle, October 1972, pp.56-63.

The extent to which cyclic patterns in the ice-cover variations in Arctic seas correspond to atmospheric pressure cycles is investigated. The basic feature of the manifestation of pressure cycles in the ice-cover coefficient is the fact that fluctuations in the pressure field, even if they are synchronized over large distances, may lead to different ice conditions in two apparently similar cases. From the fact that the ice-cover coefficient is determined by the pressure gradients, and not directly by pressure, it follows that the effect of pressure cycles upon ice coverage is determined not by the extent of each individual cycle but by the nonuniform distribution of the cycle amplitude in space; the higher the non-uniformity, the greater the pressure gradient and the more pronounced the cyclic pattern in the ice cover, and vice versa. The 27-mo variation of the pressure gradient between two points in the Arctic is analyzed for various curves. An explanation is provided for the fact that well-formed cyclic variations of atmospheric pressure have, at best, an insignificant effect upon ice cover; of how cyclic variations in ice cover are produced by slight pressure changes; and why, in certain cases, the sign of the correlation between cyclic pressure and ice cover is reversed.

# 6. Shipping Routes

## A. St. Lawrence Seaway

Adams, C.E., Jr., **Saint Lawrence Seaway system plan for all-year navigation, Appendix C, Environmental Impact**, ARCTEC, Inc., Columbia, Maryland, and Saint Lawrence Seaway Development Corp., Washington, D.C., Report No. RE-0105-7-App-C, August 1975, 85 pp.

Volume IV, Appendix C, Environmental Evaluation-Presents the results of a brief analysis of the environmental impact of each measure proposed to remove the constraints to navigation identified in the study.

Dionne, J.C., **Notion of ice-foot with special reference to the Saint-Laurent Estuary**, NTIS #ADA-056 041, May 1978, 31 pp., refs., Translation from *Cahiers de geographic de Quebec*, Vol. 17, No. 14, September 1973, pp. 221-250.

In the first part, a review of the existing definitions and classification of the icefoot is made, showing that the icefoot notion is inaccurate, often ambiguous, and not the same for everyone. In the second part, a definition and a description of the icefoot in the St. Lawrence Estuary are offered. Two main types of icefoot are distinguished: the upper and the lower strand icefoot. The protective and the morpho-sedimentological role of this feature is also emphasized.

Frankenstein, G.E., Mellor, M., Vance, G.P., and Wuebben, J.L., **An investigation of ice clogged channels in the St. Marys River**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Contract MIPR-X-70099-882249-3B, March 1978, 73 pp.

This study addresses itself to the problem of removing brash ice from Frechette Point to Six-Mile Point of the Little Rapids Cut of the St. Marys River system. The area and river system are described and estimates are made for partially clearing a channel 250 ft wide. Rough costs, based on dollars per horsepower, indicate that it would cost between 1 and 2 million dollars per clear channel mile per year.

Lewis, J.W., **Saint Lawrence Seaway system plan for all-year navigation, summary report**, ARCTEC, Inc., Columbia, Maryland, and Saint Lawrence Seaway Development Corp., Washington, D.C., Report No. TR-0105-7, July 1975, 48 pp.

This report describes a systems analysis of the problems and factors that adversely affect or halt navigation on the St. Lawrence River between Montreal, Quebec, and Lake Ontario, during the winter season. The objective of the study was to develop a plan which if implemented would provide cost-effective navigation of the system in winter. This was accomplished by developing a mathematical simulation of the Seaway operations and using this model to identify in time and space the constraints to winter navigation. Once identified, alternative system plans were developed to remove these constraints and associated cost and performance data were estimated. This information was then used in conjunction with benefits data (provided to this study) to conduct a benefit-cost analysis of each alternate plan. The study is presented in five (5) volumes. *Volume I*, SUMMARY REPORT, *contains the essential* points of the study. It describes the approach taken and major results and provides recommendations for future action. It is intended to serve as an executive summary and therefore stands complete by itself.

Lewis, J.W., **Saint Lawrence Seaway system plan for all-year navigation - Appendix A - Methodology**, ARCTEC, Inc., Columbia, Maryland, and Saint Lawrence Seaway Development Corp., Washington, D.C., Report No. TR-0105-7-App-A, July 1975, 385 pp.

Volume II, Appendix A - MATHEMATICAL FUNCTIONS AND DETAILED METHODOLOGY - Contains the detailed development of all mathematical models used in the Seaway simulation, the data base used by these models and, where pertinent, verification of the models.

Lewis, J.W., **Saint Lawrence Seaway system plan for all-year navigation - Appendix B - Seaway Simulation**, ARCTEC, Inc., Columbia, Maryland, and St. Lawrence Seaway Development Corp., Washington, D.C., Report No. TR-0105-7-App-B, July 1975, 206 pp.

Volume III, Appendix B, SEAWAY SIMULATION - Describes the computer program developed to simulate winter operation of the Seaway. It contains program descriptions, listing, flow charts, and describes input and output data. Portions of this document are not fully legible.

Lewis, J.W., **Saint Lawrence Seaway system plan for all-year navigation - Appendix D - Economics**, ARCTEC, Inc., Columbia, Maryland, and Saint Lawrence Seaway Development Corp., Washington, D.C., Report No. TR-0105-7-App-D, July 1975, 276 pp.

Volume V, Appendix D, ECONOMICS - Describes the engineering calculations and cost estimates associated with each measure proposed to remove a constraint to navigation, the cost estimates associated with each system plan alternative, and the methodology and results of the benefit/cost analysis.

Wilson, E.E., *Mariners Weather Log,* Vol. 17, No. 3, May 1973, 83 pp.

In addition to its usual sections on hints to the observer, tips to the radio officer, new items on the editor's desk, marine weather reviews, and the marine weather diary, there are included three articles: **Sea Ice, Part I Major Features and Physical Properties; Great Lakes - St. Lawrence Seaway Navigation Season Extension; and Great Lakes Navigation Season, 1972.**

## B. Great Lakes

Anonymous, **Ice conditions in areas adjacent to the North Atlantic Ocean from July to September 1977**, *Marine Observer*, Vol. 48, No. 259, January 1978, pp. 37-41.

Ice edges, sea surface and air temperatures, and surface-pressure anomalies are discussed with meteorological charts used as reference. July showed no marked anomalies of pressure or air temperature, with ice meltings generally ahead of normal. In Aug. pressures and temperatures were slight. Ice in the Greenland Sea disappeared and ice break-up over northern Canada continued ahead of normal. Ice was slow to clear off Baffin Island. Hudson Bay showed the main anomaly for high pressure in Sept. Changes in ice formations were slight except in some channels of the Arctic Archipelago where ice spread E ahead of normal and E of Baffin Island where ice remained when it is usually clear.

Assel, R.A., **Great Lakes ice cover-winter 1971-72**, National Ocean Survey, Lake Survey Center, Detroit, Michigan, Report No. NOAA-TM-NOS-LSC-D-6, October 1972, 61 pp.

Thirty-five ice charts were produced from data collected on 23 Lake Survey Center ice reconnaissance flights made on the winter of 1971-72. In addition, five summary ice charts, illustrating ice distribution patterns for short intervals during the winter over the entire Great Lakes, were produced from Lake Survey Center, United States Coast Guard, and Canadian ice reports. Freezing degree-day accumulations indicate that the 1971-72 winter was severe on western Lake Superior and near normal throughout the remainder of the Great Lakes. Ice formation was reported November 10 in western Lake Superior at Duluth Harbor and along the perimeter of all the Great Lakes by the end of January. The period of maximum ice cover varied from the second week of February to the last week of March for individual lakes.

Assel, R.A., **Great Lakes ice thickness prediction**, *Journal of Great Lakes Research*, Vol. 2, No. 2, Shelburne, Ontario, December 1976, pp. 248-255, refs.

Weekly ice thickness data, collected from 24 bay, harbor, and river sites on the Great Lakes, were correlated with freezing degree-day accumulations to develop regression equations between ice thickness and freezing degree-days. The data base at the ice measurement sites was 3-8 winters in length. The standard error of estimate varied for the individual regression equations and averaged between 7-8 cm for the five forms of regression equations. Because the regression equations are empirical, the range of input data used to predict ice thickness should be limited to the range of values used in the derivation.

Assel, R.A., Boyce, D.E., Leshkevich, G.A., Quinn, F.H., and Snider, C.R., **Summary of Great Lakes weather and ice conditions, winter 1976-1977**, National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Lab., Ann Arbor, Michigan, Rept. No. NOAA-TM-ERL-GLERL-20, October 1978, 155 pp.

The winter of 1976-77 was the fifth coldest in the past 200 years. Record-breaking low temperatures from mid-October to mid-February, associated with an upper air pressure pattern consisting of a strong ridge in the westerly flow over North America, resulted in extraordinary ice cover on the Great Lakes. Ice was produced almost simultaneously in various shallow protected areas of the Great Lakes in early December. The progression of early winter, mid-winter, and maximum ice extent was from 4 to 5 weeks earlier than normal. At the time of maximum ice extent in early February, Lake Superior was approximately 83% ice covered; Lake Michigan over 90%; Lake Huron approximately 89%; Lake Erie 100%; and Lake Ontario approximately 38%. Spring breakup started in late February in the southern part of the Great Lakes region and in early March in the northern part. The bulk of the ice cover was gone by the fourth week of April. Shipping was severely hampered by the abnormally large amount and duration of the ice cover. Direct icebreaker assistance by the U.S. Coast Guard was up about 55% over the previous winter season.

Baker, D.G., **Objective prediction of ice formation, freeze-up and break-up on the Great Lakes**, *Journal of Applied Meteorology*, Vol. 15, No. 10, October 1976, pp. 1033-1040, refs.

Objective predictions of first permanent ice formation and freeze-up on the Great Lakes were made by use of cumulative freezing degree-day totals, by the Lisitzin-Rodhe-Bilello equation, by use of departures from normal air temperature, and by use of 30-day temperature outlooks. The four objective methods yield similar improvement over use of the mean date of freeze-up in prediction of these ice events, although freezing degree-day totals appear to represent the best method. Lake Superior ice cover can be predicted by using the freezing degree-day method extrapolated to mid-lake locations with better results than a climatological prediction based on the use of long-term mean freeze-up dates. Ice breakup on the Great Lakes was predicted by using thawing degree-day totals and a correlation between stations approach. Both of these predictive techniques are superior to the use of the mean date of breakup as a prediction.

Bitting, K.R., **Ice buoy demonstration program**, Coast Guard Research and Development Center, Groton, Connecticut, Report No. CGR/DC-15/75, June 1975, 32 pp.

The objectives of the ice buoy demonstration project, supporting the Great Lakes Season Extension Demonstration program, were to test and evaluate modified standard Coast Guard aids-to-navigation buoys for use in the Great Lakes during the winter navigation season. Four standard lighted buoys were modified to increase survivability in the ice. The success of a buoy/mooring is a function of both the buoy shape and ice conditions at the deployment location.

Boyce, D. and DeWitt, B., **Great Lakes ice season, 1974-1975**, *Mariners Weather Log*, Vol. 19, No. 5, Washington, D.C., September 1975, pp. 277-282.

The first year-round navigation season was achieved on April 1, 1975 as a result of generally warmer-than-normal air temperatures in the area, below-normal ice cover, and a $.7 million government expenditure on extended season navigation. Weather conditions during the fall, winter, and spring are described, and shipping operations and losses are detailed. Data are provided in tabular form on 1) departures from normal of Great Lakes air temperature for the 1974-1975 season, by month and lake; 2) maximum accumulated freezing degree days by station; and 3) ice breaking assistance for FY 1975, by operational hours, mission in miles, total tonnages of vessels assisted, and value of cargos carried.

Bryan, M.L., and Larson, R.W., **Study of fresh-water lake ice using multiplexed imaging radar**, *Journal of Glaciology*, Vol. 14, No. 71, 1975, pp. 445-457, refs., In English with French and German summaries.

The study of ice in the upper Great Lakes, both from the operational and the scientific points of view, is receiving continued attention. Quantitative and qualitative field work is being conducted to provide the needed background for accurate interpretation of remotely sensed data. The data under discussion in this paper were obtained by a side-looking multiplexed airborne radar (SLAR) supplemented with ground-truth data. Because of its ability to penetrate adverse weather, radar is an especially important instrument for monitoring ice in the upper Great Lakes. It has previously been shown that imaging radars can provide maps of ice cover in these areas. However, questions concerning both the nature of the surfaces reflecting radar energy and the interpretation of the radar imagery continually arise. This analysis of ice in Whitefish Bay (Lake Superior) indicates that the combination of the ice-water interface and the ice-air interface is the major contributor to the radar backscatter as seen on the imagery. At these frequencies, the ice has a very low relative dielectric permittivity (<3.0) and a low loss tangent. Thus, this ice is somewhat transparent to the energy used by the imaging SLAR system. The ice types studied include newly formed black ice, pancake ice, and frozen and consolidated pack and brash ice. Although ice thickness cannot be measured directly from the received signals, it is suspected that, by combining the information pertaining to radar backscatter with data on the meteorological and sea-state history of the area, together with some basic ground truth, better estimates of the ice thickness may be provided. In addition, certain ice features (e.g., ridges, ice-foot formation, areas of brash ice) may be identified with reasonable confidence. There is a continued need for additional ground work to verify the validity of imaging radars for these types of interpretations.

Clapper, R.T., Jr., Smith, D., Stortz, K., and Sydor, M., **Ice growth studies in Duluth-Superior Harbor 1974-75**, University of Minnesota, Duluth, National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Lab., Ann Arbor, Michigan, Grant No. NOAA-04-5-022-13, September 1975, 70 pp.

This study concerns the investigation of the growth and heat budget in the Duluth-Superior Harbor. The harbor, located at the extreme western end of Lake Superior, is one of the major shipping ports on the Great Lakes. It is ice bound from mid-December to mid-April, causing cessation of interlake shipping in the winter months. The lake ice does not pose a severe navigational problem until ice packing occurs due to prolonged easterly winds in the early spring. Initial investigation on the feasibility of winter shipping in Duluth resulted in installation of an experimental bubbler system that was devised to keep the channels open in the early winter. However, the physical principles governing the ice growth in the harbor are complex and not well understood. Problems arising in ice growth forecasting, design and construction of ice retarding methods, and evaluation of the environmental implications of winter shipping require a detailed investigation on the physical processes and the heat budget for the entire harbor.

Cooper, D.W., Mueller, R.A., and Schertler, R.J., **Measurement of lake ice thickness with a short-pulse radar system**, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, Report No. NASA-TN-D-8189; E-8573, March 1976, 25 pp.

Measurements of lake ice thickness were made during March 1975 at the Straits of Mackinac by using a short-pulse radar system aboard an all-terrain vehicle. These measurements were compared with ice thicknesses determined with an auger. Over 25 sites were explored that had ice thicknesses in the range 29 cm to 60 cm. The maximum difference between radar and auger measurements was less than 9.8 percent. The magnitude of the error was less than + or - 3.5 cm. The NASA operating short-pulse radar system used in monitoring lake ice thickness from an aircraft is also described.

Dillev, J.F., **Lake Ontario ice modeling IFYGL Phase 3 Final Report**, General Electric Co., Ocean Sciences Lab., Philadelphia, Pennsylvania, National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Lab., Ann Arbor, Michigan, Report No. 76SDR2209, June 1976, 79 pp.

Ice formation, growth, and decay on Lake Ontario is simulated on two scales: a small, local, near-shore scale and a whole lake scale. A previously developed and recently improved two dimensional, time dependent, near-shore ice model is used to simulate the ice episodes during the IFYGL winter (1972-73). Each surface heat transfer mode is separately computed so that their effect on the ice cover can be quantitatively evaluated. It was found that the convective flux dominated the heat loss during the freezing periods and that it was usually twice as large as the evaporative loss. The solar flux usually dominated the heat gain during the melting periods. The computed ice thicknesses compared very well with the closest available ice thickness data. On the whole lake scale, a locally one dimensional form of the model was used to compute the various heat transfers including latent heat as a function of depth at four stations with individual meteorological and radiation inputs.

Dozier, J., Marsh, B.D., and Marsh, W.M., **Formation, structure, and geomorphic influence on Lake Superior icefoots**, *American Journal of Science*, Vol. 273, No. 1, New Haven, Connecticut, January 1973, pp. 48-64.

The long, narrow, continuous ridges of grounded ice, separated by broad areas of low relief ice, which parallel much of the shoreline of Lake Superior and other Great Lakes, are called icefoots. They form from fields of small fragments of lake ice and ball ice, which have been heaped up by storm waves and grounded. Once stabilized, an icefoot can continue to grow by wave overwash and wave spray. A sequence of up to four ridges of successively-increasing size generally forms during the winters, and the outermost ridge is subject to wave action, both erosional and depositional, most of the time. Seismic refraction and drilling show that the subsurface configuration of the ridges is often irregular, while that of the interridge ice is smoother. The total thickness of an ice ridge may exceed 11 m. Icefoots are best developed off sandy, equilibrium shorelines with high exposure to storm waves. They may form on sandbars, but the sandbars are also common in interridge areas. In plan view, the lakeward edge of an icefoot is wavy, and the amplitude-wavelength ratio is greater for icefoots off bedrock cliff shores than for those off sandy, equilibrium shores. No simple relationship exists between wavelengths of the ridges and wavelengths of formative waves. The icefoots are of geomorphic importance, as they protect the shoreline from the high-energy waves of winter and spring, thereby reducing erosion rates that otherwise might be expected. The net sediment transport along the southeastern shore of Lake Superior is about 11 times greater than that along selected segments of the Arctic shoreline, where icefoot formation is known to occur, but is less than that along comparable ice-free coasts.

Frisch, J.V. and O'Dell, J.E., **Great Lakes water levels, an update: beat the Seaway freeze**, *NOAA Magazine*, Vol. 6, No. 1, January 1976, pp. 32-37 and 38-39, University of Michigan, Ann Arbor, National Oceanic and Atmospheric Administration, Office of Sea Grant, Rockville, Maryland.

Included in the booklet are reprints of two articles. The first discusses the water levels of the Great Lakes in the threat of severe damage from storms as a result of the high water level. The second article discusses the freezing along the Great Lakes. A system of predicting or forecasting freezeup to provide for better navigation is discussed.

Lind, A.D., **Ice development on Lake Champlain**, University of Vermont, Remote Sensing Lab., Burlington, Contract No. NAS5-21753, July 1973, 5 pp.

The author has identified the following significant results. Only one usable ERTS-1 scene was available for lake ice survey of Lake Champlain. The January 8, 1973, coverage (image no. 1169-11521) revealed the presence of various ice tones, patterns, and arrangements as well as open water. MSS band 5 imagery provided the most useful data. While it was not possible to differentiate open water from one - two day old ice, which only occurred over a small portion of the lake area, it was possible to interpret the tonal signatures of the frozen portion in terms of freezing history or age. The dark gray-tones of new, smooth ice contrasts with the medium gray-tones of older ice, and the rough texture of wind-jammed bay ice. Mapping of these patterns seems quite feasible with moderate enlargement of the scene (2X to 3X).

Linklater, G.D., **The 1971-72 Great Lakes ice season**, *Mariners Weather Log*, Vol. 17, No. 1, January 1973, pp. 15-16, National Weather Service, Detroit, Michigan.

The Great Lakes 1971-72 ice season was notable for an unseasonably warm fall and early winter, with an abrupt reversal in January to a colder than normal regime, which persisted through midspring. The winter navigation season was again extended through January, and the navigation season was opened fairly early in the spring with the aid of intensive icebreaking operations conducted by United States and Canadian icebreakers. The St. Lawrence Seaway officially shut down December 15, but the locks were kept open an additional week. Conditions were bad in early March and navigation over the upper Lakes was maintained with difficulty through April and early May.

Perham, R.E., **Ice and ship effects on the St. Mary's River ice booms,** *National Hydrotechnical Conference (3rd)*, 30-31 May 1977, Quebec, Proceedings, Universite Laval, Canadian Society for Civil Engineering, 1977, pp. 419-433, 5 refs., In English with a French summary.

The St. Mary's River connects Lake Superior with Lake Huron. It contains many navigation improvements that make it an important commercial shipping route. The operation of ships in winter under a federal program to extend the navigation season has led to troublesome ice movements and accumulations. To help counteract these effects, two ice booms with a 250 foot (76 m) wide navigation opening between their adjacent ends were installed at the southerly outlet from the harbor at Sault Ste. Marie, Michigan and Ontario. The ice booms contained six force measuring devices. Records of these forces and pertinent data on the weather, water levels, ship passages, and ice conditions were kept the following winter of 1975-76. The ice booms reduced the harbor ice losses to an acceptable level and provided much information about the interactions between itself and the ice cover and the ships. Ships and environmental effects kept the ice behind the west boom free from shore much of the winter. The maximum in the east boom was an impact load of about 160,000 lbs (712 kN). The forces associated with ship passages averaged 25,000 lbs (111 kN).

Renaud, F., **Winter energy requirement of an open water channel in the Gulf of St. Lawrence,** *Atmosphere*, Vol. 15, special issue, Toronto, 1977, pp. 34-35, abstract only.

The available heat energy of the Gulf of St. Lawrence in the fall was calculated. From these calculations, potential open water sites were selected. At locations along the Laurentian Channel, winter energy budget calculations were made for an open water lead by means of a computer model. Ice was not permitted to form and, when the limiting temperature of -1.5°C was reached, mixing of water from below was induced. It was found that if the heat from the deep Laurentian Channel was not spread over a large portion of the Gulf, it was sufficient to prevent the ice formation even under severe meteorological conditions such as during the winter of 1971-1972 along the Laurentian Channel between Gaspe and Anticosti Island to Cabot Strait. For sites in the estuary, the available energy did not seem large enough to extend the open water season later than early March. For average winter temperature, however, the total winter loss was approximately 20% less than during the cold winter of 1971-72. This makes it more feasible for the deepest section of the estuary to remain ice free during a whole winter. Also, early fall mixing from below the cold intermediate layer was effective since it delayed the onset of estuary ice by more than three weeks.

Rogers, J.C., **Long-range forecasting of maximum ice extent on the Great Lakes,** National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Lab., Ann Arbor, Michigan, Report No. NOAA-TM-ERL-GLERL-7, January 1976, 20 pp.

A technique, based on prewinter thawing and wintertime freezing degree-days, has been developed for making long-range forecasts of the percent maximum ice extent on the Great Lakes. The number of thawing degree-days is known by early winter, but the crux of the technique is to predict the number of freezing degree-days that will accumulate by March 3, the average date of maximum ice extent on the Lakes during the last 13 winters. This was accomplished by using an average March 3 accumulated freezing degree-day value from both the large and small ice extent winters between 1962-63 and 1968-69, which alternate in a quasi-biennial cycle. The equations and freezing degree-day prediction method were then used to hindcast maximum ice extent on the Lakes during the winters 1969-70 to 1974-75.

Rondy, D.R., **Great Lakes ice atlas,** Lake Survey Center, Detroit, Michigan, Report No. NOAA-TM-NOS-LSCR-1, September 1971, 52 pp.

A series of 33 charts is presented to illustrate the ice cover on the Great Lakes for three classifications of winter: mild, normal, and severe. Six ice charts are provided for each of the Great Lakes. Two charts show the maximum extent of ice cover during a mild and severe winter and four charts are classified as normal. The percent of lake surface that can be expected to become ice covered during a normal winter is: 60 percent Superior, 40 percent Michigan, 60 percent Huron, 98 percent Erie, and 15 percent Ontario. Mid-winter ice thicknesses can range from 36 inches (91 cm) along the north shore of Lake Superior to 4 inches (10 cm) during a mild winter on the lower lakes.

Rondy, D.R., **Great Lakes ice cover, winter 1967-1968,** United States Lake Survey, Detroit, Michigan, Rept. No. BD-5-4, September 1968, 68 pp.

The report describes the U.S. Lake Survey's 1967-68 aerial ice reconnaissance program and presents 47 ice charts produced from data collected on 14 flights. A brief description of ice conditions on each of the Great Lakes and a summary of weather conditions is included.

Rondy, D.R., **Great Lakes ice cover, winter 1968-69,** Lake Survey Center, Detroit, Michigan, Report No. NOAA-TM-NOS-LSCD-1, October 1971, 50 pp.

Twenty-three ice charts were produced from data collected on eight reconnaissance flights made during the 1968-69 winter ice season. Ice formation was first reported on December 9, 1968. Areas reporting extended from Duluth, Minnesota, on western Lake

Superior, to Barcelona, New York, on the south shore of Lake Erie. Winter temperatures generally varied from slightly above normal in the Lake Superior region to slightly below normal on Lake Erie. During the period of maximum ice cover, 40 percent of the surface of Lake Superior was covered.

Rondy, D.R., **Great Lakes ice cover, winter 1969-1970**, Lakes Survey Center, Detroit, Michigan, Report No. NOAA-TM-LOS-LSCD-3, March 1972, 61 pp.

Thirty-three ice charts are produced from data obtained on fourteen aerial reconnaissance flights made during the 1969-1970 ice season. Winter temperatures are classified as below normal and were determined from freezing degree-day accumulations. Reported dates of first ice varied from November 3, 1969, on southern Lake Huron to December 23, 1969, on eastern Lake Ontario. The period of maximum ice cover varied across the Great Lakes, as did the areal extent of the ice cover. The reported dates of last ice ranged from March 31 at Tibbetts Point on eastern Lake Ontario to April 27 at Point Iroquois on eastern Lake Superior.

Sydor, M., **Western Lake Superior ice**, University of Minnesota, United States Geological Survey, Professional Paper No. 929, 1976, pp. 169-172.

The more frequent coverage by ERTS-type spacecraft of Lake Superior ice as a possible aid in ice forecasting is discussed. Forecasting of ice growth and predicting ice packing are generally based on considerations of heat budget for the ice sheet. The required measurements of light albedo for the entire ice cover can be made accurately from ERTS data, which also make it possible to delineate the severely packed ice. An estimate of the fraction of the ice cover on the western arm of Lake Superior displaying highly packed characteristics is presented. The corresponding values for the volume of the lake ice, estimated from heat-budget considerations and ERTS data, permit a rough calculation of the average thickness of the icepack blocking the shipping lanes.

United States Lake Survey, **Great Lakes - St. Lawrence Seaway navigation season extension**, *Mariners Weather Log*, Vol. 17, No. 3, 1973, pp. 135-139, Detroit, Michigan.

The Winter Navigation Board, a multiagency organization, has initiated a Winter Navigation Program to study and test the feasibility of means to extend the navigation season for the Great Lakes and St. Lawrence Seaway. The ultimate objective is to determine the possibility of guaranteed year-round navigation. Even limited success in extending the navigation season should have a definite economic impact in the Great Lakes area.

Wilson, E.E., **Great Lakes navigation season, 1976**, *Mariners Weather Log*, Vol. 21, No. 3, Washington, D.C., May 1977, pp. 155-168, Environmental Data Service, NOAA, Washington, D.C.

There was continuous traffic through the Great Lakes system in 1976. The U.S. Soo Lock system on the St. Mary's River remained in operation during the entire year. The Canadian Soo Lock opened on April 5. The St. Lawrence Seaway and Welland Canal target opening date was April 3 because of adverse weather and ice conditions. Weather and ice services were provided as needed throughout the entire 1976 season with continued navigation. This was the second year in a row that navigation proceeded without a break in the upper Great Lakes. The scheduled closing dates of December 18 for the St. Lawrence Seaway and December 30 for the Welland Canal were delayed until December 24 and January 3, 1977, respectively, by exceptionally severe ice conditions throughout the Great Lakes-St. Lawrence Seaway system. Final passages through the Seaway were the latest since it began service. Again, December led with most days with high winds, and November had the most observations. January produced the highest wind (56 knots, recorded by the G.M. HUMPHREY on Lake Huron). The seas were 10 feet. The four high-wave reports of 16.5 feet were on Lake Erie (which had two), Lake Huron, and Lake Superior. Some of the more severe storms are described.

Wilson, E.E., *Mariners Weather Log*, Vol. 21, No. 6, November 1977, 78 pp., National Oceanic and Atmospheric Administration, Environmental Data Service, Washington, D.C.

In addition to its regular sections, this issue contains the following articles: **SEASAT-A and NIMBUS-G aplications to marine weather: Hong Kong as a typhoon haven;** and **Great Lakes ice season.**

# 7. Ice Terminology

Armstrong, T.E. and Roberts, B., **Illustrated ice glossary**, *Polar Record*, Vol. 8, No. 52, 1956, pp. 4-12.

Armstrong, T.E. and Roberts, B., **Proposed new terms and definitions of sea ice for the use of submarines**, *Polar Record*, Vol. 12, No. 77, 1964, pp. 197-198.

Since submarines started operations under sea ice, it has become apparent that the existing ice glossaries are inadequate to meet requirements. A variety of new terms have been coming into use on both sides of the Atlantic. These lacked systematic coordination with each other and with existing terms. It seemed to us the agreement should be sought before two different sets of terms became firmly established. The following draft terms and definitions have resulted. These are worded as suggested additions and amendments to Part I of our **Illustrated ice glossary**, *Polar Record*, Vol. 8, No. 52, 1956, pp. 4-12. We invite comments either informally or to be published as letters to the Editor.

Boyle, R.J., **Ice glossary**, U.S. Navy Electronics Laboratory, San Diego, California, 10 June 1965, 44 pp., 5 refs.

Department of Transportation, Meteorological Branch, **Abridged international ice nomenclature**, 1957, Canada, Developed and approved by the World Meteorological Organization.

*Manual of Standard Procedures and Practices for Ice Reconnaissance*, 3rd edition, Toronto, Canada, 1965.

World Meteorological Organization, **Illustration of the international ice nomenclature**, 1957, sets of illustrations obtainable from Fotchaus Friedrich Kunze, Hamburg 36, Stephansplatz 2.

# 8. Ice Breakers

Anonymous, **A brief history of the ice-breakers of the United States Coast Guard**, *Marine Observer*, Vol. 48, No. 261, July 1978, pp. 127-131.

The USCG's need for icebreakers dates back to the purchase of Alaska in 1867. An original prototype, the barquentine BEAR, incorporated auxiliary steam engines, hoisting screw, and hull planking sheathed with ironbark or greenheart, along the waterline to withstand the scoring action of ice. The stem was plated with iron. The NORTHLAND, in many ways modeled after the BEAR, was equipped with a steel hull and a cut-away bow, which aided navigation through fields of broken ice. The extensive experience of the USCG in Arctic regions coupled with the increased use of barges to transport fuel in the U.S. pinpointed the need for vessels that could actually break through ice barriers. The RARITAN and NAUGATAUK, completed in 1939, were the first USCG cutters designed for icebreaking activities. They were single-screw, diesel-electric vessels of 110-foot length that could break sheet ice 20 in. thick without charging and ramming. The needs of World War II precipitated the construction of the four heavy-duty Wind Class icebreakers - the NORTH WIND, SOUTH WIND, EAST WIND, and WEST WIND - capable of breaking through and withstanding the pressure of polar ice. Three of the four Wind Class vessels were delivered to Russia under the Lend-Lease Program in 1944. The EAST WIND was the only sea-going, deep-draught icebreaker owned by the U.S. when World War II ended. During World War II, icebreaker construction activity was governed by both the USN and the USCG. In the 1960's the USCG was granted sole authority over operations of icebreakers in polar regions. Two new and sophisticated icebreakers, POLAR STAR and POLAR SEA, were launched in 1976 and 77. Propelled by combined diesel or gas turbine engines, they can break ice N21 ft thick. They also function as research vessels for meteorological, oceanographic, and other scientific pursuits.

Anonymous, **Fighting ice**, *Ocean Industry*, Vol. 13, No. 10, October 1978, pp. 144-146, refs.

Research efforts of the Arctic Petroleum Operators' Association are discussed in connection with a project that studied crater, bench, and controlled splitting blasting as well as blasting in water under ice. The project also endeavored to develop a lightweight shothole drill for placing charges, to determine load factors for ice during bench blasting, and to ascertain if ice islands become unstable under shock loading. Crater blasting is the best way to destroy ice islands, and placing charges under ice is the best method for destroying ice sheets in rivers and lakes. Techniques used in blasting ice islands are outlined. A slurry explosive with a 1.45 specific gravity in a 29-ft diameter spherical cavity is recommended. Bench blasting and controlled splitting need too much explosive to be effective. Ice destruction can also be effected through the use of such gases as ammonia, hydrogen chloride, sulfur dioxide, and volatized ammonium chloride. This method is intended for small scale applications and includes the following operations: drilling holes in icebergs to allow the anchoring of a towing system; the drilling of a cavity for explosive demolition of icebergs; deicing of surface areas on ships; and the slotting of ice sheets for such projects as pipelaying and deicing of canal locks. The salting effect on water produced when using the gas destruction method prevents refreezing. More development work is still needed for this method but researchers are convinced of its effectiveness.

Boyle, R.J., **Ice glossary**, U.S. Navy Electronics Laboratory, San Diego, California, 10 June 1965, 44 pp., 5 refs.

No abstract.

Breslau, L.R., Edwards, R.Y., Jr., Farmer, L.D., Goettel, F.A., Johnson, J.D., McIntosh, J.A., Richmond, C.A., and Super, A.D., **Development of arctic sea transportation**, *Journal of the Marine Technology Society*, Vol. 4, No. 5, September-October 1970, pp. 17-68, 84 refs.

This article pertains to design criteria, ships, transportation, research projects, sea ice composition, ice physics, meteorological factors, ice surface features, remote sensing, ice breaking, and icebreakers.

Dalzell, J.F. and Nowacki, H., **Engineering and economic feasibility study of roll stabilization and heel inducing systems for new Coast Guard polar icebreakers**, Vol. 1, Hydronautics, Inc., Laurel, Maryland, Report No. TR-762-1-Vol-1, February 1968, 94 pp.

This report summarizes studies of various roll stabilization and heeling systems for a new polar icebreaker design. Though the functions to these two systems are distinct, they may be studied as one larger system because there exist many technical similarities and some possible opportunities for physical combination. Selection of criteria for both subsystems is discussed herein and a number of preliminary system designs are developed and evaluated. A final comparison of all designs is made and the advantages and disadvantages discussed. It is concluded that for the present icebreaker application, systems involving

stabilizer and heeling system concepts that differ in principle from recent practice in this country have no compelling advantages.

Faddyeer, O.V., Kashtelyan, V.I., Yagodkin, V.Y., and Yvlin, A.Y.R., **Icebreakers**, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1973, Report No. 418.

The book **Ledokoly** (Icebreakers) generalizes the experience that has been accumulated in the development and design and arrangement features and points out paths toward further improvement. All present Soviet and foreign icebreakers are described, their operating conditions are analyzed, the basic ice performance characteristics of an icebreaker are examined (ice speed to power ratio, ice strength, maneuverability, jamming conditions), and methods of evaluating these qualities, developed by Soviet specialists, are set forth; the design features of the basic machinery and system of icebreakers are noted; recommendations on their design are presented. A considerable part of the book is devoted to features of the choice of hull shape, main dimensions, and power plant. Data on icebreaker hull design and relations for determining the strength dimensions of the framing and plating are presented. The operating conditions of the electric power plant are analyzed and diagrams of the electric power plants of icebreakers presently in operation are presented; requirements imposed on these diagrams are formulated. Features of the design and calculation of special icebreaker systems (list and trim systems, engine cooling systems, hydraulic systems) are discussed. Materials on certain general ship systems (towing, steering, and helicopter systems) are presented. Features of an icebreaker control system are described and the prospects and trend of its development are discussed.

Habercom, G.E., Jr., **Icebreakers and ice breaking**, (citations from the NTIS data base), National Technical Information Services, Springfield, Virginia, December 1978, 200 pp.

The design and performance of icebreakers, ice breaking, ice navigation, and ice distribution are reviewed in these Government-sponsored research reports. (This updated bibliography contains 213 abstracts, 10 of which are new entries to the previous edition.)

Lecourt, E.J., Lewis, J.W., and Scoville, F.W., **Icebreaker propulsion system simulation, Phase II, Dynamics of AC-DC icebreaker propulsion systems**, Office of Engineering, U.S. Coast Guard, Washington, D.C., October 1967, 101 pp.

This report discusses the simulation of a diesel electric propulsion system for an icebreaker using AC generators and rectified DC for the propulsion motors. A comparison is made between an icebreaker using this system and one using a more conventional electric propulsion system.

Lecourt, E.J., Lewis, J.W., and Scoville, F.W., **Icebreaker propulsion system simulation, Phase III, Propulsion system behavior during propeller-ice interactions**, Office of Engineering, U.S. Coast Guard, Washington, D.C., December 1967, 67 pp.

This phase of the Icebreaker Propulsion System Simulation reports on the results of studies directed at improving the overall in-ice icebreaker performance through improved propulsion system design. A mathematical description of the ice-torque problem for dynamic and quasi-steady state behavior is presented, and additional propulsion system electrical circuit dynamics necessary to more adequately describe propulsion system dynamic behavior during propeller-ice encounters are described. The predicted performance of the USCGC GLACIER when subjected to the ice load torque model is presented. A load control scheme (designed to extend the constant horsepower range of the propulsion system well below bollard propeller speed) is developed and incorporated into the basic system equations. The performance of a system of the same size as the GLACIER incorporating this load control system and subjected to the same ice loads is also presented. It is concluded that the incorporation of a load control system significantly increases the capability of the icebreaker propulsion system when operating in ice.

Lewis, J.W., **Ship design and maintenance computer program (icebreaker propulsion system simulation, diesel-electric)**, Office of Engineering, U.S. Coast Guard, Washington, D.C., 27 May 1968, 266 pp.

This program solves numerically the set of simultaneous non-linear differential equations that describe the dynamic behavior of the complete propulsion system (including vessel dynamics) of a diesel-electric icebreaker during maneuvering. The program also contains a means of subjecting the propeller to ice impact loadings of the user's making. At the option of the user, input data can readily be printed for documentation purposes and output data can be plotted.

Mentz, P.B., **Improving ship operations in ice covered waters**, *Journal of the Marine Technology Society*, Vol. 8, No. 1, January 1974, pp. 54-57.

Full-scale testing was performed during this past winter on the air coating system, which was conceived to improve the performance of ships operating in broken ice and mush ice. The Great Lakes ore carrier LEON FRASER was modified to accept this system after model tests had been used to optimize the design. A relatively mild winter resulted in insufficient build-up of broken ice in the channels to effectively test the system. The data that was obtained indicated that a potential exists for the air coating system to reduce resistance in broken ice and mush ice. Measurements were also made of ice forces on the

hull structure caused by impacting sheet ice and by hitting ice floes. Results of these measurements have led to the development of predictor equations for calculating ice forces.

**New vessels for ice navigation in Canada,** *Arctic,* Vol. 1, No. 2, 1948, pp. 119-121.

This article deals with additions being made to vessels employed in ice-filled seas around Canada.

Steinert, H., **LNG through the North-West passage: German technological preparations for the Arctic,** *Northern Offshore,* Vol. 7, No. 4, April 1978, pp. 29-30.

Plans to transport LNG from the west side of the Arctic archipelago to the eastern coast of America require further knowledge of ice technology. Efforts of the Federal Republic of Germany to develop large LNG tankers with ice breaking capabilities are described. The Hamburg Shipbuilding Experimental Station (HSVA) and a coordinate institute in Leningrad put into service the first ice testing basin for ship development. As of April 1978, no consistent observations were available regarding the relationship between a ship's speed and ice thickness where ice breaking is concerned. The properties of sea ice are discussed and evaluated. In the spring of 1977, a Russian ice breaking supply ship, WERRATOR, was sent on a 4-mo experimental voyage to Spitzbergen. Along with a bow thruster and twin screw variable pitch propellers, a jet mantle proved to be the decisive factor in the ice breaking process. The jet mantle protects the propeller blades from ice damage. Another important factor was the Jastram-HSVA air-water nozzle that was tested on the WERRATOR trip. From the bow of the ship a jet of water mixed with air is directed aft at about the waterline level, and with such force that it increases propulsion power and ice breaking capability by 20%. The air/water nozzle device is compared to a unit using only compressed air as a shield and is more efficient overall. Other tests conducted that involved basic research in ice technology are discussed. Once they are completely evaluated, they should provide much information as to the best construction of LNG tankers destined to travel through the North-West Passage.

Sterrett, K.F., **The arctic environment and the arctic surface effect vehicle,** Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-76-1, January 1976, 33 pp.

This report summarizes the advances in understanding of the Arctic that have come about since the inception of the ARPA Arctic Surface Effect Vehicle Program in 1970, primarily as the result of CRREL's participation. Major efforts to increase knowledge of sea ice, terrestrial, and coastal topographic features are described. Special emphasis is placed upon the quantitative understanding of pressure ridging. Other areas of major interest are atmospheric characteristics and ecological effects. A list of publications generated is included.

Voelker, R.P., **Research plan for arctic ship powering and development,** Arctec, Inc., Columbia, Maryland, and Maritime Administration, Washington, D.C., Report No. 416C-3, 12 December 1977, 58 pp.

This study examines and documents the basis for an Arctic surface ship transportation system and identifies the major elements of a research program designed to upgrade the state-of-the-art of Arctic marine transportation technology in order to minimize its risk and improve its attractiveness as a viable alternative to other modes of transportation.

Welsh, J.P., **Projected commercial maritime activity in the Western Arctic,** Coast Guard Research and Development Center, Groton, Connecticut, Report No. CGR/DC-27/77, October 1977, 79 pp.

Commercial marine activity will increase dramatically in the western Arctic commencing about 1980. This is based on the projected rate and extent of exploitation of the natural resources (particularly petroleum). The consequence of increased maritime traffic will be continued growth of demand for the marine services provided by the U.S. Coast Guard. The services required are primarily in the areas of ice breaking, search and rescue, aids to navigation, and marine environmental protection. To meet these demands, a Polar Vessel Information System will have to be developed and operated by the U.S. Coast Guard.

# 9. Surface Vehicles

Abele, F. and Brown, J., **Arctic transportation: operational and environmental evaluation of an air cushion vehicle in northern Alaska,** *Journal of Pressure Vessel Technology*, Vol. 99, No. 1, February 1977, pp. 176-182, 8 refs.

Traffic tests conducted near Barrow, Alaska, with a 7-ton SK-5 Air Cushion Vehicle have shown that these types of vehicles can provide year-round high-speed transport capability over a variety of relatively level, low strength terrains. The ecological impact of ACV traffic over easily degradable tundra terrains is not nearly as significant as that of wheeled or tracked vehicle traffic.

Ackley, S.F., and Hibler, W.D., III, **Sea ice terrain model and its application to surface vehicle trafficability,** *Journal of Terramechanics*, Vol. 12, No. 3/4, December 1975, pp. 171-190, 16 refs.

Pressure ridges are the primary obstacle to the movement of amphibious surface vehicles travelling over the Arctic ice pack. Ridge height and spacing data can now be obtained with remote sensing methods and used to construct a realistic three-dimensional ridge model for sea ice terrain. This model can be used to perform trafficability analyses. The results, when combined with vehicle characteristics, can be used to predict vehicle operational performance. There is good agreement between predictions from the model and from simulated routes through sea ice areas selected from aerial photographs. The terrain model is also useful for mapping regional variations in ridge characteristics throughout the Arctic Basin. The paper also discusses the nature of the rugged shear zone in the offshore region, and the presence of leads caused by dilation of the ice pack in strong weather systems.

Nakano, Y. and Smith, M., **Model analysis of vehicle trafficability with application to surface effect vehicles on sea ice fields,** NTIS #AD-737 601, January 1972, 17 pp., 3 refs.

Efforts were made to derive the design criteria of surface effect vehicles operated on Arctic sea ice. Statistical theories were developed to describe trafficability of the vehicles and topography of the sea ice. By the use of actual sea ice surface profiles obtained by an aerial laser profiler, the usefulness of the present statistical method was demonstrated.

Vance, G.P., **Modeling systems for vessels in ice,** University of Rhode Island, Department of Ocean Engineering, Kingston, and Office of Research and Development, U.S. Coast Guard, Washington, D.C., Doctoral thesis, June 1975, 367 pp.

The report covers the existing methods utilized in scaling model data for vessels in ice to the full-scale regime. It reviews the properties of model and full-scale ice. The main thrust of the report is the development of a procedure for testing vessels in model ice and scaling the results to the full-scale regime with an accuracy of plus or minus 10 percent. The second section of the report discusses the design of a test facility to conduct icebreaking and hydrodynamic model tests. All the data collected and utilized are contained in appendices to the report.

# 10. Icebreaking Techniques

Anonymous, **Dome Petroleum - challenge and opportunity**, *Canadian Shipping and Marine Engineering*, Vol. 50, No. 2, November 1978, pp. 14-19, no refs.

A summary of Dome Petroleum operations in the Canadian Arctic is presented. Estimates of the oil and gas reserves in the Arctic region showed a total of N90 billion barrels of recoverable oil and N620 trillion of recoverable gas, based on the estimated yield of oil and gas/mi3 of sediment. Recent geophysical surveys in the Sverdrup Basin indicated that this region may contain the largest reserve potential in the Arctic Islands. Dome's exploratory program over the next 5 years contemplated drilling 15 wells. The Beaufort Sea is covered with ice for 8-9 months each year. The ice is subdivided into 3 zones - a permanent polar ice pack to the N, shorefast ice nearshore from October to January, and a transient ice zone, which is ice-free 3-4 months of each year. Dome and Canadian Marine Drilling operate a fleet of 3 drillships, 7 ice breaking supply boats, 3 ocean-going barges, and a large supply vessel. The vessels are drilling in 100-200 feet but can drill in 60-1,000 feet of water. Dome was developing a new drillship with a Canadian Arctic Class 10 hull and an ice-removing mooring system, extending its drilling season substantially in the Beaufort Sea and year-round in the inter-island area of the high Arctic. Potential surpluses are given. Studies of North Sea operations have led to the development of an early production system similar to those used in the early development of the North Sea. Dome was expected to use Class 10 vessels to transport their oil and gas. The market value of the oil and gas and the impact of the investments on the Canadian economy are discussed.

Ashton, G.D., **Evaluation of the ice management problems associated with the operation of a mechanical ice cutter on the Mississippi River**, NTIS #ADA-002 058, October 1974, 37 pp., 29 refs.

The study concentrates on effects occurring after the cutting operation. Included in the evaluation are assessments of refreezing rates, movement and disposition of the slabs produced by the cutting, and an examination of effects related to ice jams. The evaluation is specific to the upper Mississippi River, in particular Pool 19 above Lock and Dam 19 at Keokuk, Iowa. It was found that most ice production during a winter occurs during a small fraction of the period of ice cover; hence removal after these short periods may allow navigation to proceed for significant wintertime periods. A relation was found between cut slab dimensions and critical velocity to move them that will enable estimates to be made of accumulation. Breakage of adjacent ice by vessel waves was found to impose a possible restraint on vessel speed but not a serious one.

Ashton, G.D., DenHartog, S.L., and Hanamoto, B., **Icebreaking by tow on the Mississippi River**, NTIS #AD-768 169, August 1973, 70 pp.

A field investigation of icebreaking by the motor vessel RENCE G. operating on the Mississippi River betweel Alton, IL, and Fort Madison, IA, is reported. The operation encountered a wide variety of ice conditions and was performed with a variety of barge configurations and arrangements. Important qualitative observations of the nature and difficulties encountered while icebreaking were made and, by instrumenting the propeller shafts and using load cells between the towboat and the barges, quantitative information was obtained on the resistance encountered while icebreaking. Also described are the effects of repeated passage through an ice cover, navigation procedures peculiar to icebreaking, and minor damage sustained by the towboat.

Ashton, G.D., **Numerical simulation of air bubbler systems**, *National Hydrotechnical Conference (3rd)*, 30-31 May 1977, Quebec, Proceedings, Universite Laval, Canadian Society for Civil Engineering, 1977, pp. 765-788, 7 refs., In English with a French summary.

The use of air bubbler systems to suppress ice formation is a technique that has been applied in a variety of situations and with varying degrees of success. Recently two-dimensional line source bubbler systems were analyzed (Ashton, 1974) in an effort to make available a tool that may be used in the design of a bubbler installation. That analysis was a steady-state evaluation of the melting state of an ice cover above a bubbler system predicted on the basis of input variables (depth, air discharge rate, water temperature). In actual operation, however, a bubbler "sees" changing conditions such as a diurnal and longer-term weather conditions, varying water temperatures, and depletion of the available thermal reserve. The simulation presented herein uses the steady-state analysis developed earlier (Ashton, 1974) and steps it in time with each new condition determined from the results of the previous time step. In this sense the analysis herein may be considered quasi-steady. Results of the simulation are presented for an example case for a winter in Duluth, Minnesota, and illustrate selection of time step size, effect of various strategies of intermittent operation, and variation in width of open water area with changing weather conditions.

Assur, A., **Problems in ice engineering**, *Inter-*

*national Symposium on Ice Problems (3rd)*, 18-21 August 1975, Hanover, New Hampshire, Proceedings, International Association of Hydraulic Research, 1975, pp. 361-372, 6 refs.

The design of large structures in ice-infested water such as piers, off-shore terminals, and platforms, is subject to considerable uncertainties due to lack of suitable data and experience. However, observations on ships provide clues for some of the most serious problems to be solved. This paper discusses the effect of friction, adfreezing, side pressure, and forces on random ice agglomerations. Horizontal ice pressure can stop ships, so can "ice pillows" under moderate ice conditions.

Buzuev, A.I., and Ryvlin, A.I., **Calculating ice resistance to icebreaker movement under various ice conditions**, *Problemy Arktiki i Antarktiki sbornik statei*, Vol. 31, 1969, pp. 69-73, In Russian.

This article pertains to sea ice, icebreakers, ice navigation, and ice cover strength.

Decker, J.L., **The application of air cushion configurations to icebreaking**, Maritime Administration, Office of Commercial Development, Washington, D.C., Report No. 110, July 1978, 208 pp.

The objective of the project was the quantitative evaluation of the cost and effectiveness of air cushion configurations in icebreaking applications with displacement ships in level ice fields. Simple theoretical methods were developed for the prediction of the air cushion icebreaking capability in the low speed and high speed icebreaking modes. Conceptual designs for air cushion icebows and air cushion icebreakers were prepared and the economic analysis of their use with the displacement ships is reported. The self-propelled air cushion icebreaker was determined to provide more flexible operational capability and was more cost effective for the cases examined.

DenHartog, S.L., **SS MANHATTAN tests: a review of the ice program**, *International Conference on Port and Ocean Engineering under Arctic Conditions (1st)*, Proceedings, Vol. 1, 1971, pp. 101-111, 2 refs.

The U.S. Army Cold Regions Research and Engineering Laboratory was contracted by Humble Oil Company to plan and supervise the ice testing aspects of their arctic tanker tests aboard the SS MANHATTAN. Since the prime purpose of the entire test program was to derive thrust and resistance values for varying ice types, USACRREL's responsibility was to define the ice conditions encountered. While the ship was underway in ice, a continuous description (log) of ice conditions, speed, propeller rpm, etc., was maintained. For formal tests, ice thickness was measured at adequate intervals to define the sheet over the test section. Total channel width, size of cusps, and other parameters were also noted. The major effort for formal tests was to measure the ice strength to enable comparison of tests in floes of equal thickness. Temperature and salinity profiles of the ice sheet were taken, which could be used indirectly to measure ice strength. Brazil tensile tests were made to measure the strength directly but, as with all small sample ice testing, there was a large scatter in the results. A least squares fit of the Brazil data vs brine volume as determined from the temperature salinity measurements gives the following relationship: Brazil tensile strength in kg/sq cm is equal to 4.82 minus 5.68 times the square root of the brine volume. To compare the strength of one ice sheet to another for purposes of correlating ship tests it appears that brine volume measurements should be used rather than small sample tests. Although the relationship between brine volume and strength is not precisely known, there is far less scatter in the brine volume measurements.

Frankenstein, G.E. and Smith, N., **Use of explosives in removing ice jams**, *Symposium on Ice and its Action on Hydraulic Structures*, 7-10 September 1970, Reykjavik, Iceland, International Association for Hydraulic Research, 1970, 10 pp., 6 refs.

A brief history of the use of explosives for ice jam removal is discussed. Ammonium nitrate mixed with fuel oil is considered the best explosive for ice jam control because of its cost and safety features. For maximum effect, the charge should be placed in the water below the ice. A curve is included that gives maximum crater hole diameter as a function of the cube root of the charge weight.

Gagnon, F. and Mellor, M., **Cutting ice with high pressure water jets**, NTIS #AD-766 172, 1973, 22 pp., U.S. Coast Guard, Report No. USCG-D-15-73, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

The report describes high pressure water jet ice cutting experiments conducted in support of the Coast Guard domestic icebreaking program. The test objectives were to determine power requirements for cutting two feet of fresh water ice at a speed of advance of 5 knots. The results of the tests show extremely high power requirements even when using state-of-the art equipment pumping at 100,000 psi.

Hess, R.V., Lucht, R.A., and Saunders, A.R., **A technique for breaking ice in the path of a ship**, National Aeronautics and Space Administration, Langley Research Center, Langley Station, Virginia, Report No. NASA-CASE-LAR-10815-1, 10 March 1972, 11 pp.

A technique is described for breaking ice in the path of a ship. A laser is placed on the bow of the ship with apparatus to scan the ice in the path of the ship with the laser beam. The beam cuts or shatters the ice, enabling the ship to break the ice in its path.

IAkovlev, G.N., **Breaking ice with a jet of gas**, NTIS #AD-768 827, August 1973, 16 pp., 4 refs., For Russian original see CRREL #26-1977.

Thermodynamic methods are currently being applied successfully in industry for breaking rocks. These same methods have been examined for breaking ice. However, for large scale operations the use of a gas jet does not appear promising because of the large amount of energy required to melt ice.

Kovacs, A., and Mellor, M., **Breakage of floating ice by compressed gas blasting**, NTIS #AD-755 504, December 1972, 41 pp., 15 refs.

Tests were made to determine the effectiveness of compressed-gas blasting devices for breaking floating ice sheets. Experiments were made on frozen lakes in New Hampshire and Alaska using the Cardox and Airdox blasting systems, and comparative tests were made with conventional chemical explosives. Gas blasting devices were found to be closely comparable to chemical explosives in terms of specific energy consumption, but absence of any significant shock wave in the gas blast results in a different mode of action. The gas devices fractured the ice largely by flexure, giving large fragments. Practical applications of gas blasting for ice breaking are discussed.

LaGarde, V., Mock, S.J., and Tucker, W.B., **Arctic terrain characteristics data bank**, Cold Regions *Research and Engineering* Lab., *Hanover*, New Hampshire, Report No. CRREL-TR-247, March 1974, 47 pp.

An arctic terrain characteristics data bank was established as part of a program to evaluate advanced surface effect vehicle (SEV) designs for arctic use. The data bank contains approximately 4300 kilometers of terrain profiles in digital form acquired with an airborne laser profilometer system, and approximately 50 digital terrain maps for areas ranging from 0.01 sq km to 1 sq km, photogrammetrically derived from aerial photography. The development and data processing techniques are described along with descriptions of the data bank contents.

McFadden, T. and Stallion, M., **1974 ice breakup on the Chena River**, NTIS #ADA-018 352, October 1975, 46 pp., refs.

The Alaskan Projects Office of USA CRREL made a detailed study of the ice breakup. Ice thicknesses were measured at specific locations on the Chena River, from its confluence with the Tanana River upstream to the first bridge on the Chena Hot Springs Road. Average ice thicknesses were computed as well as average ice volumes per mile of river length. Water temperatures and velocities were measured at different locations on the river. Aerial and ground reconnaissance was maintained on the river during the breakup period, and ground parties were dispatched to almost all ice jams observed on the river. Comparisons to other years' breakups were made, and it was concluded that the 1974 breakup was extremely mild.

Mellor, M., **Cutting ice with continuous jets**, *International Symposium on Jet Cutting Technology (2nd)*, 2-4 April 1974, Cambridge, England, Proceedings, 1974, pp. G5/65-76.

The practicality of cutting ice with continuous water jets has been investigated by laboratory experiments and field tests, using nozzle pressures from 2500 to 100,000 lbf/sq. in (17.2 to 690 MN/sq. m), traverse speeds from 0 to 357 ft/min (0 to 1.8 m/sec), and nozzle diameters from 0.008 to 0.023 in. (0.203 to 0.584 mm). Special emphasis has been given to a study of the feasibility of using water jets to supplement the performance of icebreaking vessels. While the "non-contact" aspect of a jet tool is attractive, power requirements for deep penetration at high traverse speeds are exorbitant by comparison with the power requirements for competing cutting systems. Application of test data in design calculation for other cutting applications is discussed.

Nikolaev, S.E., **Cutting sea ice by directed blasting**, NTIS #AD-768 829, August 1973, 20 pp., 5 refs., For Russian original see CRREL #26-1979.

The utilization of directed blasting can prove a very effective means in solving a number of practical problems: the creation in the pripay (fast shore ice) of ice-free channels for the passage of ships with weak hulls, for laying pipes or cable from the ice surface, and so forth. Placing the charges according to a prescribed system and exploding them through brief time intervals in a fixed sequence can assure the directed removal of ice along the given direction.

Peschanskii, I.S., **Methods of disrupting an ice cover**, NTIS #AD-720 073, 1971, 63 pp., Translation from*Ledovedenie i ledotekhnika*,2nd ed., Leningrad, Gidrometeoizdat, 1967, pp. 308-367.

For solving the problems in ice technology, it is necessary to resort to the engineering methods of breaking down an ice cover, predetermined by the features of the water basin and the purposes of the tasks that are being conducted. In this report, the following problems are discussed: disruption of ice cover during cruising of ships in ice; disruption of ice barriers; protection of structures and ships; creation of conditions favoring a delay in the ice formation process; removing the ice and snow from water basins; and cutting holes around ships.

Shvaishtein, Z.I., **Cutting ice with a continuous high-pressure water jet**, NTIS #AD-769 721, August 1973, 11 pp., 8 refs., For Russian original see CRREL #26-1978.

In a study of the possible techniques of cutting ice by an "icecutter," it was clarified that, in addition to the mechanical devices for cutting and breaking down

the ice, it is feasible to utilize a high-pressure water jet. The possibility of the utilization of such jets is particularly important for cutting relatively thick ice (from 0.5 m and more) since the mechanical means (disk cutters, etc.) are fairly complicated. During the movement of the icecutter, from a hydrocompressor mounted on the ship through shaped nozzles, we feed continuous high-pressure jets with which a number of parallel blocks are cut.

Sinotin, V.I., **Recommended practice for combatting ice jams**, NTIS #AD-769 723, August 1973, 106 pp., 48 refs., Translation of **Metodicheskie ukazaniia po bor'be zatorami i zazhorami l'da**, Leningrad, *Energiia*, 1970.

Because ice jams and floods resulting from them are dangerous and often economic disasters and because they are a part of the life cycle of most rivers in the USSR, methods have been developed to control them. Various measures can lessen the effects of these jams: eliminate the conditions that form the jams; accurately predict the location and intensity of ice jams; destroy those already formed. Recommended practices for destroying or preventing jams are: dusting ice covers to weaken them; use of mechanical devices to cut or break the ice; straightening river channels; aerial surveys and bombing; use of explosives; protection and proper design of hydraulic structures; and controlling the flow and temperature of the currents to inhibit ice formation.

Yakovelev, G.N., **Breaking ice with a jet of gas**, Cold Regions Research and Engineering Lab., Hanover, New Hampshire, Report No. CRREL-TL395, August 1973, 19 pp., Draft translation of Arkticheskii i Antarkticheskii Nauchno-Issledovatelskii Institut, *Trudy*(USSR), Vol. 300, 1971, pp. 153-167.

Thermodynamic methods are currently being applied successfully in industry for breaking rocks. These same methods have been examined for breaking ice. However, for large scale operations the use of a gas jet does not appear promising because of the large amount of energy required to melt ice.

# 11. AIDJEX Reports

Ackley, S.F., Campbell, W.J., Hartwell, A.D., Hibler, W.D., III, Kovacs, A., and Weeks, W.F., **Investigations performed on the Arctic Ice Dynamics Joint Experiment, March 1971**, NTIS #AD-775 381, December 1973, 66 pp., refs.

This report is in five parts. Part I, Mesoscale Strain Measurements on the Beaufort Sea Pack Ice discusses fracture orientations in correlation with strain rate ellipse. Part II, Structure of a Multiyear Pressure Ridge, discusses transverse profile measurement of a ridge. Part III, Top and Bottom Roughness of a Multiyear Ice Floe, is a spectral study of snow and ice topography. Part IV, Airphoto Analysis of Ice Deformation in the Beaufort Sea gives time, direction, and magnitude of deformational motion along with mesoscale measurements of strains. Part V, Data on Morphological and Physical Characteristics of Sea Ice in the Beaufort Sea, discusses measurement of ice blocks in ridges and of salinity and temperature.

Maykut, G.A., Thorndike, A.S., and Untersteiner, N., **AIDJEX (Arctic Ice Dynamics Joint Experiment), Part I, Scientific Plan (second draft)**, Division of Polar Programs, National Science Foundation, Office of Naval Research, Washington, D.C., and University of Washington, Seattle, Contract No. NSF-C625, May 1970, 54 pp.

An array of drifting stations, consisting of a central manned station surrounded by four unmanned and four manned stations, is proposed to conduct measurements of the large-scale response of sea ice to its environment in the Arctic Ocean. Additional unmanned stations will be deployed outside the main array. A logistic headquarters based on a secure location is required. Position, atmospheric pressure, and wind speed will be determined regularly at all stations. In addition, observations at the manned stations will include meteorological conditions, wind stress, water stress, and ice conditions. Surface observations will be supplemented by regular airborne surveys of the test area by means of photography, side-looking radar, laser profiler, and infrared imagery. Under-ice topography will be obtained by submarine transits. A pilot study is proposed.

Trowbridge, R., **The Arctic Ice Dynamics Joint Experiment (AIDJEX)**, *Naval Research Reviews*, Vol. 29, No. 5, May 1976, pp. 8-17.

The Arctic Ice Dynamics Joint Experiment (AIDJEX) is a U.S.-Canadian cooperative research program aimed at advancing man's understanding of the large-scale response of sea ice to its environment. The dynamic ice model being developed by AIDJEX will be an important step towards understanding the long term climatic interaction between one atmosphere, cryosphere, and hydrosphere and provide a comprehensive analysis of the role of ice-covered seas in world climate. In addition, AIDJEX is yielding scientific and technical information in the fields of energy transfer in a predominantly stable atmospheric boundary layer, heat and momentum exchange in the upper ocean, sea ice morphology, pressure ridging mechanics, and data buoy technology.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 1, September 1970, 41 pp.

The Arctic ice dynamics joint experiment is a common purpose and a cooperative effort to understand quantitatively the interaction between the fields of motion of the atmosphere, the pack ice, and the liquid ocean. This understanding is basic to forecasting ice conditions and to assessing variations in surface/atmosphere heat exchange and their relation to variations in general atmospheric circulation.

University of Washington, Seattle, Division of Marine Resources, (Fletcher, J.O. and Johnson, A.), *AIDJEX Bulletin*, No. 2, **Theoretical discussions**, October 1970, 75 pp.

Contents: The kinematics and mechanical behavior of pack ice; The state of the subject; Latest experiments with ice rheology; Notes on a possible constitutive law for Arctic Sea ice; Thoughts on a viscous model for sea ice; The pressure term in the constitutive law of an ice pack; A study of ice dynamics relevant to AIDJEX; Techniques for measuring strain rate; Power spectrum analysis of ice ridges.

University of Washington, Seattle, Division of Marine Resources, (Fletcher, J.O. and Johnson, A.), *AIDJEX Bulletin*, No. 3, **Selected Soviet research, November 1970**, 133 pp.

The United States shares with the USSR many scientific problems in the Arctic Basin, and many of our approaches to common problems are similar to theirs. For example, the first article in the issue describes an AIDJEX-like field experiment conducted by the USSR in 1961. In recent years, both countries have increasingly emphasized the dynamics of ocean/atmosphere interaction in the Arctic. This has been reflected in the USSR by the establishment of a separate Department of Ocean/Atmosphere Interaction in the Arctic and Antarctic Scientific Research Institute.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 4.

Contents: AIDJEX Oceanographic Investigations; A Report on the 1970 AIDJEX Pilot Study; 1971 AIDJEX Water Stress Pilot Studies Introduction; Lamont Measurements of Water Stress and Ocean Currents; University of Washington Water Stress Studies.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 5, **1971 Pilot studies - remote sensing and ice morphology**, February 1971, 67 pp.

This Bulletin describes in detail the remote-sensing and ice morphology pilot studies, follows with a summary of study plans, and concludes with an account of the Numerical Modeling Working Group session held in November. In general, these pilot studies aim to define more adequately the appropriate time and space scales of measurements for the main AIDJEX experiment in 1973. They also aim to reveal information on representativeness of stress measurement and the best methods for obtaining them. These pilot studies should thus provide essential information for refining and simplifying the design of the main experiment.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 6, **Ice dynamics**, March 1971, 51 pp.

The report contains several papers related to ice motion. The first paper describes an experiment to measure the surface tilt of an ice-covered ocean using a hydrostatic leveling system. The second paper discusses the distribution of ice (by age, thickness, and hummockedness) in the Arctic resulting from accumulation, ablation, and export of ice. The third and fourth papers are translations of Soviet research on ice floe motion and the drift of ice fields. Also included in the Bulletin are abstracts of two papers dealing with thermodynamic modeling of sea ice.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 8, **Pilot study narratives, 1971**, May 1971, 41 pp.

During March and April of 1971, coordinated AIDJEX pilot studies were conducted in the Beaufort sea. AIDJEX Bulletin No. 8 contains narratives describing how these studies were carried out. The following studies were conducted: a combined CRREL-USGS-NASA program of complementary remote sensing overflights and ground truth investigation; a study of ocean currents, conducted by the Lamont-Doherty Geological Observatory of Columbia University; a program of oceanographic measurements, conducted by the University of Washington Department of Oceanography; and an air-ice boundary layer study, conducted by the Arctic Submarine Lab of the Naval Undersea Center. A report on the logistics of the pilot study is also included.

University of Washington, Seattle, Division of Marine Resources, (Johnson, A.), *AIDJEX Bulletin*, No. 9, **AIDJEX planning conference**, August 1971, 44 pp.

AIDJEX Bulletin No. 9 contains a condensed account of a conference held on June 21-22, 1971 to review recent progress toward the scientific goals of AIDJEX and to discuss plans for the 1972 pilot experiment. Progress to date in numerical modeling of the ocean-ice-atmosphere system is discussed. Proposed experiments for the pilot study were reviewed. Areas in which notable progress has been made and areas that require special attention are mentioned. Also included is an explanation of AIDJEX organization.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 10.

Bulletin No. 10 is a cover-to-cover translation (by Joachim Beuchner) of Volume 296 of *Transactions (Trudy) of the Arctic and Antarctic Scientific Research Institute*, published by the Hydrometeorological Press, Leningrad, in 1970. With this issue, the AIDJEX Bulletin continues the practice (begun in Bulletin No. 3) of translating and making available to American scientists reports of foreign research in areas of interest to AIDJEX.

University of Washington, Seattle, Division of Marine Resources, (Johnson, A.), *AIDJEX Bulletin*, No. 11, November 1971, 47 pp.

AIDJEX Bulletin No. 11 outlines the plans for the 1972 AIDJEX pilot study, to be conducted during March and April 1972, on the pack ice in the Beaufort Sea approximately 400 km north of Pt. Barrow, Alaska. The content and objectives of the planned observational program (which consists of standard meteorological and oceanographic observations, in addition to air stress, water stress, radiation, heat budget, micro- and macroscale strain measurements, acceleration, and tilt measurements) are discussed. The general logistics plan for the study is also presented. The Bulletin also contains two translations from **Problemy Arktiki i Antarktiki**, No. 38, published in mid-1971 by the Arctic and Antarctic Research Institute in Leningrad: (1) Borisenkov, E.P., and A.F. Treshnikov, **The polar experiment**; and (2) Treshinkov, A.F., E.P. Borisenov, et al., **The American Arctic Ice Dynamics Joint Experiment**. Also included is a list of items submitted by the NSF Polar Information Service for translation under the PL 480 program.

University of Washington, Seattle, Division of Marine Resources (Johnson, A.), *AIDJEX Bulletin*, No. 12, February 1972, 160 pp.

AIDJEX Bulletin No. 12 reports the preliminary results of several projects that were carried out during the 1971 AIDJEX Pilot Study (March-April 1971, in the Beaufort Sea 550 km north of Tuktoyaktuk, NWT,

Canada). These projects include a study of a multiyear pressure ridge; 25 cm coherent, synthetic-aperture radar observations of sea ice from aircraft; measurements of (atmospheric) turbulence in the near-ice layer; and water stress and ocean current measurements. Also included in the Bulletin are: a paper on water and ice motion during the 1970 AIDJEX Pilot Study (March-April 1970, Beaufort Sea); two papers on the study of sea-ice pressure ridge statistics; and the table of contents of *Trudy* (Proceedings) of the Arctic and Antarctic Research Institute, Leningrad, Vol. 303 (1971) (translation to appear in AIDJEX-72-16 and AIDJEX-72-17, AIDJEX Bulletin Nos. 16 and 17, TT 72-50022).

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 13.

Bulletin No. 13 contains three reports from CRREL on ice deformation during the 1971 AIDJEX pilot study and two reports on salinity determination from the Marine Sciences Branch of Environment Canada.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 14.

Bulletin No. 14 contains the first reports on the 1972 pilot study and position, weather, and azimuth data for all camps.

University of Washington, Seattle, Division of Marine Resources,(Maykut, G.A., Thorndike, A.S., and Untersteiner, N.), *AIDJEX Bulletin*, No. 15, **AIDJEX scientific plan**, August 1972, 73 pp.

AIDJEX Bulletin No. 15 is devoted to discussion of the scientific objective, design, and practical applications of the Arctic Ice Dynamics Joint Experiment. The main objective of AIDJEX is 'to reach, through coordinated field experiments and theoretical analyses, a fundamental understanding of the dynamic and thermodynamic interaction between arctic sea ice and its environment.' The basic questions that must be answered in order to reach this understanding are enumerated. To answer these questions, it is proposed to conduct atmospheric, oceanographic, and sea-ice observation programs from an array of manned drifting stations in the Arctic Ocean; observations made at the manned stations will be supplemented by atmospheric pressure and large-scale deformation data from unmanned data buoys deployed outside the main array. The proposed observation programs are described, as well as the objectives and problems of data management. Application of AIDJEX to sea ice modeling, ice forecasting, ice engineering, and surface transportation (among other areas) is discussed.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 16.

**Contents:** Origin of a bergfield in the northeastern Chukchi Sea and its influence on the sedimentary environment; Evolution of a large arctic pressure ridge; Simulation of sea ice dynamics during AIDJEX; An estimate of the strength of arctic pack ice; An investigation of the effect of large-amplitude ocean waves on antarctic pack ice; Sea ice properties and geometry; Sea ice conditions in the arctic; Interaction of pack ice with structures and associated ice mechanics.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 17.

Bulletin No. 17 is the second half of a translation (by the Israel Program for Scientific Translations) of Volume 303 of the Proceedings*(Trudy)*of the Arctic and Antarctic Scientific Research Institute. The first half (AIDJEX Bulletin No. 16) dealt with the computation and forecasting of ice-cover variations with problems related to ice drift. This second half covers (1) the relation of wind and pressure fields to ice coverage fluctuations, (2) the formation and deterioration of the ice cover, and (3) methodological topics connected with the study of the parameters and deformation of the ice cover.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 18, February 1973, 113 pp.

AIDJEX Bulletin No. 18 contains a variety of AIDJEX-related papers. One paper deals with the oceanographic experiments conducted during the 1971 AIDJEX pilot study to determine ice motion and interior flow field. The second paper reports on the under-ice diving experiment carried out during the 1972 pilot study. A third paper summarizes AIDJEX field operations during fall 1972, and another paper reports on an experiment in mapping the underside of sea ice by backscattered sound, which was conducted in May 1972. The bulletin also includes (1) abstracts of the papers that AIDJEX participants presented at the fall annual meeting of the American Geophysical Union (Symposium on Sea-Air Interaction in Polar Regions), December 1972; (2) some brief comments on AIDJEX by Claes Rooth, member of the NAS Joint Review Panel for AIDJEX: and (3) three papers by members of the AIDJEX modeling group that were presented at the above-mentioned symposium.

University of Washington, Seattle, Division of Marine Resources, (Johnson, A.), *AIDJEX Bulletin*, No. 19, March 1973, 150 pp.

This issue contains articles dealing with field experiments as well as theoretical studies on arctic sea ice. The first paper discusses salinity variations in sea ice, based on data collected during the 1972 AIDJEX pilot study. The second reviews the hydrographic (interior flow field) experiments conducted during the 1972 pilot study and compares their results with those obtained in 1970 and 1971. The third paper comments on the effects of skin friction and form drag on the movement of sea ice. The fourth gives an

extensive description of the mechanical kinematic model of pressure ridge formation developed by two members of the AIDJEX modeling group. The fifth paper discusses the spatial variability of topside and bottomside ice roughness and its effect on underside acoustic reflection loss, using data gathered in a continuing program by the U.S. Naval Oceanographic Office. The last article consists of an index to all digital data stored in the AIDJEX Data Bank and a preliminary user's guide to the Data Bank.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 20, May 1973, 168 pp.

AIDJEX Bulletin No. 20 contains an extensive investigation, by R.A. Brown, into planetary boundary layer dynamics. The work evaluates the methods available for predicting air stress for a synoptic-scale ice dynamics model. Also included in the bulletin are a data management report on the 1972 AIDJEX pilot study (summary of data received by the AIDJEX Data Bank from the principal investigators of the 1972 pilot study) and an index to the contents of past bulletins.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 21, July 1973, 208 pp.

Bulletin No. 21 deals mainly with continuing work on modeling the arctic ice cover and atmosphere. It contains papers dealing with such subjects as two-dimensional stress and strain-rate in a flowing ice cover, the thickness distribution of sea ice, steady drift of an incompressible arctic ice cover, mesoscale strain in sea ice, and a method for calculating boundary stress in an atmospheric boundary layer. Further work in remote-sensed data analysis is also discussed, in particular sonar mapping of the underside of sea ice and determining the pressure ridge frequency distributions from laser data. Two items of special interest are an index of all pictorial data in the AIDJEX Data Bank and a list of all AIDJEX bulletins now available from NTIS.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 24.

A model of the motion of drifting pack ice in the Arctic is presented, treating the growth and melt rates of the ice, the formation of leads and pressure ridges, and a mechanical response that is elastic at low stress levels and plastic at some higher, critical state of stress. The strength of the ice is determined by its thickness distribution, and therefore varies because of both thermal and mechanical effects. To examine the behavior of the model, several artificial calculations were made by specifying the strain rate history of a single element of pack ice and solving for the ice thickness distribution and the states of stress in the ice. This paper, written by the AIDJEX modeling group, identifies many details in the model that require further study, but concludes that the underlying physical assumptions will do. Bulletin No. 24 contains, in addition, a paper by A. Thorndike on strain and strain rate calculations based on position measurements made during the 1972 AIDJEX pilot study and a paper by R. Schwaegler on fracture in ice sheets due to isostatic shear imbalance.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 25, July 1974, 126 pp.

A variety of articles dealing with field work and data analysis as well as pack ice modeling are presented. Articles discuss suitability of the pack ice surface to vehicle travel; thickness and roughness variations of multiyear sea ice; determining dynamics and morphology of Beaufort Sea ice from data obtained by satellites, aircraft, and drifting stations; a climate simulation; model applied to arctic pack ice; and problems of structuring large capacity computer programs. An index to all ERTS-1 photographs that are presently in the AIDJEX data bank is included.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 26, September 1974, 206 pp.

AIDJEX Bulletin No. 26 contains a summary of the program and progress of AIDJEX since its organization in 1970. A logistics report from the AIDJEX Lead Experiment, which was carried out in spring 1974, is also included. Two articles describe results obtained from the 1972 AIDJEX pilot study: One deals with ocean current observations at the main camp; and the other with surface atmospheric pressure fields computed from pilot study data and National Weather Service data. Other articles deal with ice deformation obtained from satellite imagery and with further progress in numerical modeling of sea ice.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 27, November 1974, 181 pp.

The first part of AIDJEX Bulletin No. 27 covers several subjects, among them the use of satellite photographs to determine the movement and deformation of sea ice, further work on elastic strain and plastic deformation in the AIDJEX model, the goals for remote sensing during the AIDJEX main experiment, hydrostatic leveling on sea ice, and the reconnaissance of Peister's Ice Island carried out this summer by AIDJEX and the Canadian Polar Continental Shelf Project.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 28, March 1975, 184 pp.

The first articles in this bulletin describe some of the projects being undertaken during the 1975-76 AIDJEX main experiment (meteorology, air stress, oceano-

graphy, ocean and ice tilt). Other articles discuss progress and problems with the AIDJEX numerical model, data analysis, and the possibility of using geostationary satellites for communication in polar regions.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 29, July 1975, 185 pp.

Much of AIDJEX Bulletin No. 29 is devoted to further discussion of the AIDJEX sea ice model, in particular the ice-ocean momentum transfer, the planetary boundary layer parameters, and the effect of changing the yield surface. The remote sensing plan for the AIDJEX main experiment field operations from late February to early June is also included. Other articles deal with using ERTS photographs to test ice thickness redistribution, measuring the turbulent boundary layer under pack ice, and modeling the seasonal ablation and accretion of antarctic sea ice.

University of Washington, Seattle, Division of Marine Resources (Johnson, A.), *AIDJEX Bulletin*, No. 30, November 1975, 131 pp.

Bulletin 30 contains five reports from members of the modeling group. The papers discuss the effect of ice motion on the mixed layer under arctic ice, fluctuations and structure within the oceanic boundary layer below the arctic ice cover, integration of elastic-plastic constitutive laws, a difference approximation to the momentum equation, the fracture of ice sheets with part-through cracks, and the NCAR Electra flights.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 31, March 1976, 207 pp.

This bulletin contains articles on acoustic radar, resistance laws, similarity parameters in the planetary boundary layer model, energy exchange over young sea ice, velocity shear instability, gravitational stresses in floating ice sheets, oscillations and pedestaling on T-3, sea ice bottom analysis, the use of LANDSAT imagery to study sea ice drift and deformation. In addition, four preprints on ice models are included. (Portions of this document are not fully legible.)

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 32.

Bulletin No. 32, the first in a series of data reports, contains data summaries for the period 11 April-29 June 1975, an 80-day sequence. The next data report will cover the next 80 days and perhaps backtrack to catch some projects absent from this one.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 33, September 1976, 164 pp.

Bulletin No. 33 contains six papers relating to sea ice studies, one describing an atmospheric boundary layer model, and one on the finite element method. The sea ice studies include topography, dynamics, antisymmetric stress, cracking mechanism, disclinations and catastrophies in vector and tensor fields, and deformation. Also included is a summary of a master's thesis on wind and temperature profiles taken during the Arctic Lead Experiment.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 34, **AIDJEX measurements of sea ice motion**.

During 1975 and 1976 many measurements of sea ice motion were made as part of AIDJEX. Approximately 1.5 x $10^5$ determinations of latitude and longitude were recorded at 41 measurement stations in the Beaufort Sea. These data have been edited and interpolated for presentation in this report.

University of Washington, Seattle, Division of Marine Resources, *AIDJEX Bulletin*, No. 35, **Ice forecasting limitations imposed by the accuracy of atmospheric prediction models**.

Forecasts produced by the operational prediction model of the National Meteorological Center are examined for errors that may limit the accuracy of sea ice model predictions. Errors in the predicted low-level height gradients and geostrophic winds are found to be no worse in the Arctic than in most mid-latitude land areas. However, the forecast skill approaches zero by 72 hours when the errors in the predicted geostrophic winds typically become as large as the geostrophic winds themselves. It is concluded that the application of the AIDJEX model to sea ice forecasting will be limited much more severely by the accuracy of atmospheric pressure forecasts than by the formulation of the ice dynamics.

University of Washington, Seattle, Division of Marine Resources (Johnson, A.), *AIDJEX Bulletin*, No.38, March 1978, 207 pp.

Contents: The structure and evolution of flow fields and other vector fields; Response of sea ice to one-dimentional driving forces and boundary perturbations; A summary of the planetary boundary layer model for AIDJEX; Analysis of AIDJEX data from a boundary layer profiler, Spring 1976; Character of Arctic PBL structure as determined by acoustic radar; Estimation of the ocean tide from ice-surface gravity observations; The free-drift velocity field accross the AIDJEX manned camp array; Radar anistropy of sea ice due to preferred aximuthal orientation of the horizontal c-axes of ice crystals.

Weeks, W.F. and Wittman, W., **Ice mechanics and morphology working group report**, *AIDJEX Bulletin*, No. 1, September 1970, pp. 30-34, NTIS #AD-713 986.

This is a summary of the AIDJEX Working Group

meeting on Ice Mechanics and Morphology held at CRREL on 26-27 August.

# 12. Conferences and Symposia

Arctic Institute of North America, *Symposium on Remote Sensing in the Polar Regions*, 6-8 May 1968, Easton, Maryland, Sponsored in part by the Office of Naval Research, the Department of the Army, the Office of the Chief of Research of the National Science Foundation, and the Department of Interior, Geological Survey, Washington, D.C., 70 pp.

The Arctic Institute of North America has long been interested in encouraging full and specific attention to applications of remote sensing to polar-research problems. The major purpose of the symposium was to ac.,uaint scientists and technicians concerned with remote sensing with some of the special problems of the polar areas and, in turn, to acquaint polar scientists with the potential of the use of remote sensing. The symposium therefore was designed to foster an exchange of ideas between the users and potential users of remote sensing, and instrumentation and interpretation specialists.

Bishop, L.F. and Rettenmaier, W.F., Jr. (comps.), *Catalog of technical publications produced by Naval Environmental Prediction Research Facility*, NAVENVPREDRSCHFAC PUBS CATALOG No. 1, Monterey, California, September 1975.

This is a collection of 10 bibliographic notices covering papers, reports, etc., produced by the Naval Environmental Prediction Research Facility between June 1971 and June 1975. The report comprises four sections: technical papers, technical notes, computer programming notes, and technical (contract) reports. Hereafter, the listing will be published semiannually. Subjects covered by technical papers, notes, and reports include turbulence and vertical motions, weather modification, sea-air interactions, tidal and storm surge prediction, numerical weather prediction models, hail and ice growth modelling, tropical cyclones, typhoons, forecasting, ballistic wind forecasting, ship routing, sound propagation in ocean, monsoons, fog, tropical meteorology, wave heights in the North Pacific, maritime fog, fog modification, and ocean climate and structure. A large number of the papers concern typhoon forecasting.

Donehoo, I. and Hacia, H., *Guide to Soviet Literature Accessions in the Atmospheric Sciences Library and the Geophysical Sciences Library*, Environmental Data Service, Silver Spring, Maryland, Report No. WB-TA-20, 1969, 111 pp.

The *Guide to Soviet Literature Accessions in the Atmospheric Sciences Library* is prepared to aid scientists who are not well versed in Russian. The Guide makes initial access to content of Russian literature possible by presenting translated tables of contents and annotation and, on a selective basis, authors' abstracts, introductions, summaries, and conclusions.

Fletcher, J.D., *Proceedings of the Symposium on the Arctic Heat Budget and Atmospheric Circulation*, January 31 through February 4, 1966, Lake Arrowhead, California, Rand Corp., Santa Monica, California, Report No. RM-5233-NSF-Pt-1, December 1966, 346 pp.

Contents: Polar ice and climate; The Arctic heat budget and atmospheric circulation; Stochastic models of air-sea interaction and climatic fluctuation; Heat regime of the Soviet Arctic related to the main atmospheric circulation patterns and their many variations; A quantitative description of some characteristics of the general atmospheric circulation and their relation to the radiation regime of the Arctic; Evidence of climatic fluctuations on Axel Heiberg Island, Canadian Arctic Archipelago; The influence of Greenland on the general atmospheric circulation; Historical evidence of sea-level change and its relation to polar albedo; Report of working group on some issues concerning climatic change and possible ways of resolving them; Calculating thermal regime and mass budget of sea ice; Comments on the mass budget of Arctic pack ice; Characteristics of the heat exchange; Heat budget at the surface of the Arctic Ocean; Numerical characteristics of the radiation regime in the Soviet Arctic; Possible changes in the radiation budget over the polar ocean; Transfer of momentum and heat in the planetary boundary layer; Report of working group on the heat and mass budget of the pack ice; Report of working group on radiation, climate, and cloud conditions in the Arctic; Report of working group on atmospheric advection and turbulent exchange of heat, moisture, and momentum.

International Glaciological Society, *Symposium on Remote Sensing in Glaciology*, 16-20 September 1974, Cambridge, England, *Journal of Glaciology*, Vol. 15, No. 73, 482 pp.

Includes general state-of-the-art discussion following final paper abstracts and discussions of papers presented, but not published, and abstracts of papers accepted, but not presented. For individual published papers see CRREL #s 30-2325 through 30-2354.

National Research Council (Iceland), *International Conference on Sea Ice*, 1971, Reykjavik, Iceland, 309 pp.

The National Research Council of Iceland organized the conference because the increasing occurrence of drift ice around Iceland caused serious difficulties for

the country. Because the last international conference on sea ice had been held in 1958 it was felt that the exchange of ideas on an international level would be both timely and desirable. The conference was organized into seven sessions dealing with regional studies, ice observation and reporting techniques, sea ice and climate, sea ice mechanics, remote sensing, and a general topics session.

Sater, J.E., *Report of Arctic Ocean Technology Workshop held at Airlie House, Warrenton, Virginia,* Arctic Institute of North America, Report No. AINA-TR-10, December 1971, 56 pp.

The report is on a workshop held to stimulate wide discussion and innovative thought on available technology that could be useful to the Navy. Three broad areas were chosen for discussion: (1) the technology that supports science and exploration, (2) the technology that is used in transportation, communication, and logistics and (3) the technology that is utilized or is presently feasible in resource exploitation. These areas were covered in detail to expose practical usage and limitations of the technology.

Society of Naval Architects and Marine Engineers, *Ice Tech Symposium,* 9-11 April 1975, Montreal, Canada, see CRREL #s 30-1836 through 30-1850.

Analysis (mathematics); icebreakers; ice navigation; ice breaking; ice resistivity; models; design criteria; and sea ice were discussed.

# 13. Bibliographies

Aldoshin, E.I., Betin, V.V., Karakash, E.S., Kryndin, A.N., and Vladimirov, O.A., *Transactions of State Oceanographic Institute*, No. 71, Foreign Technology Division, Wright-Patterson AFB, Report No. FTD-MT-24-241-68, 4 October 1968, 216 pp., Edited machine translation of Gosudarstvennyi Okeanograficheskii Institut, *Trudy* (USSR), No. 71, 1964, pp. 5-140.

Contents: Seasonal and interannual variations in ice conditions and position of the edge of the ice in the far eastern seas in relation to peculiarities of atmospheric circulation; Method of precomputation of iciness of the sea in Okhotsk and Gulf of Tatary in the spring period; The possibility of forecasting the expansion of ice along western shores of the central Caspian Sea region; Iciness of the Davis Strait; The periodicity of variations in iciness of the Baltic Sea; Aerial photography of ice drift in the sea.

**Arctic sea ice, a selected bibliography, 1965-77**, *Glaciological Data*, 1978-GD-2, pp. 53-105 and 129-239, refs.

Contents: Bibliographies; sea ice; ice drift; freezeup; ice breakup; ice water interface; remote sensing; ice forecasting; ice air interface.

Cold Regions Research and Engineering Lab., *Bibliography on Cold Regions Science and Technology 1951-*, Hanover, New Hampshire, Several vols., later vols. designated CRREL Report No. 12, Continuing bibliography issued approx. annually.

Contents: Bibliographies; Snow; Ice; Frozen Ground; Engineering.

Cold Regions Research and Engineering Lab., *Bibliography on Cold Regions Science and Technology*, Vol. XXIII-Index, Hanover, New Hampshire, Report No. CRREL-12-Vol. 23-Index, July 1969, 234 pp.

The *Bibliography on Cold Regions Science and Technology*, CRREL Report 12, was first published in 1951 and is a continuing publication of the Cold Regions Bibliography Section in the Science and Technology Division of the Library of Congress. Bibliography on Snow, Ice, and Frozen Ground features another change in title, reflecting the somewhat expanded subject coverage, and especially the added emphasis on engineering.

Cold Regions Research and Engineering Lab., *Bibliography on Cold Regions Science and Technology*, Vol. XXIX, Part 1, Hanover, New Hampshire, Report No. CRREL-12-29-1, 1975, 288 pp.

The *Bibliography on Cold Regions Science and Technology*, CRREL Report 12, was first published in 1951 and is a continuing publication of the Cold Regions Bibliography Project in the Science and Technology Division of the Library of Congress. It is sponsored by and prepared for the Cold Regions Research and Engineering Laboratory (formerly Snow, Ice, and Permafrost Research Establishment) of the U.S. Army Corps of Engineers. With Volume 20 the title was changed to Bibliography on Snow, Ice and Frozen Ground, with Abstracts, and with Volume 23 the current title was adopted. The present volume contains material accessioned between July 1974 and June 1975. The volume consists of two parts, each separately bound. Pt. 1 contains the full citation of 4032 items, in many cases with abstracts.

Cold Regions Research and Engineering Lab., *Bibliography on Snow, Ice and Permafrost with Abstracts*, Vol. 16, Hanover, New Hampshire, 1962, Report No. CRREL-12.

Dunbar, M.J., *Marine Transportation and High Arctic Development: A Bibliography*, Canadian Arctic Resources Committee, Ottawa, 1980, 162 pp.

The bibliography deals with scientific and technical research relevant to the development of marine transportation in the Canadian North.

Ficke, E.R. and J.F., *Ice on Rivers and Lakes - A Bibliographic Essay*, Geological Survey, Water Resources Division, Reston, Virginia, Report No. USGS/WRD/WRI-78/025 and USGS/WRI-77-95, October 1977, 181 pp.

Ice on rivers and lakes influences design and construction of structures, operation of shipping, flow and circulation, water quality, and other factors related to the use of the water. Human interest in understanding these influences has led to many programs of data collection, research, and investigations for a century or more. The body of literature reporting on these studies includes several thousand items in textbooks, proceedings, journals, and technical reports. By far, the largest portion of the studies were in the United States, Canada, or the Soviet Union. The literature can be classified as dealing with basic characteristics of ice; freezing and melting processes and their prediction and control on rivers and on lakes; effects of river and lake ice on navigation, flow, and structures; and influences of ice on chemical, biological, and thermal aspects of water quality. This bibliography cites 750 publications.

Habercom, G.E., Jr., *Icebreakers and ice breaking (A Bibliography with Abstracts)*, National Technical Information Service, Springfield, Virginia, December

1975, 117 pp.

The design and performance of icebreakers, ice breaking and navigation, and ice distribution are reviewed in these Government-sponsored research reports. (This updated bibliography contains 112 abstracts, 23 of which are new entries to the previous edition.)

Habercom, G.E., Jr., **Icebreakers and ice breaking**, National Technical Information Service, Springfield, Virginia, December 1978, 72 pp.

The design and performance of ice breaking, ice navigation, and ice distribution are reviewed in these reports gathered in a worldwide literature survey. (This updated bibliography contains 66 abstracts, 5 of which are new entries to the previous edition.)

Haynes, F.D., *Survey of Design Criteria for Harbors and Channels in Cold Regions - An Annotated Bibliography*, NTIS #ADA-025 226, March 1976, 32 pp.

A world-wide review of the literature applicable to the design of harbors and channels in cold regions was conducted. Forces due to ice movement present the dominant factor in the design of marine structures in cold regions. Expressions for calculating the ice criteria such as construction materials, structure geometry, and methods of ice suppression are discussed.

National Environmental Satellite Service, **Publications and Final Reports on Contracts and Grants, 1973-NESS**, Washington, D.C., Report No. NOAA-TM-NESS-55, April 1974, 15 pp.

The memorandum is one of a series containing lists of articles and reports published by or for the National Environmental Satellite Service. To date the series consists of NESC TM 1 (for 1958-66), 2 (1967), 11 (1968), 22 (1969), 31 (1970), 38 (1971), and 46 (1972). This issue lists items published or received during 1973 and includes items omitted from previous issues.

National Environmental Satellite Service, **Publications and Final Reports on Contracts**, Washington, D.C., Report No. NOAA-TM-NESS-69, April 1975, 14 pp.

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# 14. Bibliography of Bibliographies

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This list was compiled by N. Dumont, CRREL Librarian, with the help of Dr. G. Thuronyi of the Library of Congress.

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Bubbling, icebreakers.
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Marine transportation, ice conditions, icebreakers, ice navigation, channels (waterways), hydraulic structures, marine engineering.
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Includes discussions. Models, ships, ice navigation, icebreakers, ice cover, thickness, arctic regions.
28-4007

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28-573

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Icebreakers, bubbling, lubricants.
28-611

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Ships, ice navigation, ice loads, motion studies, analysis (mathematics).
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28-1559

**On the calculation of the side shell plating for the effect of an ice load,** Faddyeer, O.V., Solostianskii, D.I., and Teqkaera, T.Kh., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, *Ice Navigation Qualities of Ships,* Edited by D.E. Kheisin and IU.N. Popov, pp. 180-199, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i antarkticheskii nauchno-issledovatel'skii institut, *Trudy,* Vol. 309, 1973.
Icebreakers, design criteria, ice cutting, ice loads, impact strength, analysis (mathematics).
28-1551

**Determination of the ice loads on an icebreaker's hull with consideration of reflected impact,** Popov, IU.N., et al, U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, *Ice Navigation Qualities of Ships,* Edited by D.E. Kheisin and IU.N. Popov, pp. 100-114.

**Strain-gauge tests of icebreaking transport vessels,** Likhomanov, V.A. and Solostianskii, D.I., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, *Ice Navigation Qualities of Ships,* Edited by D.E. Kheisin and IU.N. Popov, pp. 128-135, NTIS #AD-764 807, Translation from Leningrad, Arkticheskii i antarkticheskii nauchno-issledovatel'skii institut, *Trudy,* Vol. 309, 1973.
Ships, icebreaking, ice loads, impact strength, ice navigation, tests, test equipment.
28-1554

**Calculating drag of an icebreaker moving in an ice-filled channel,** Zefirov, A.S., *Sudostroenie,* No. 9, Sept. 1973, pp. 11-12, 1 ref., In Russian.
Icebreakers, ice cover thickness, ice strength, ice loads, analysis (mathematics).
28-2037

**Observation data on the speed of ship movement in ice-covered sea**, Romanov, A.A., **Sovetskaia antarkticheskaia ekspeditisiia, 1955-**, *Trudy*, No. 59, 1973, pp. 86-94, In Russian.
Ice navigation, sea ice distribution, ice cover thickness, icebreakers. The speed of the ships OB and PROFESSOR VIZE were calculated in ice-covered waters. The speed of the PROFESSOR VIZE in the Davis Sea following the OB was 9.5 knots in ice of 1-3 marks, 6.5 knots in ice of 4-6 marks, 5 knots in ice of 7-9 marks. The OB attained 3.5 knots in another area in ice of 9-10 marks and 2.2 knots in ice of 10 marks at full power. The variety in ice conditions according to region is described.
28-2402

**Effect of "ice pillow" formation with icebreakers moving through young autumn ice**, *Problemy Arktiki i Antarktiki, Sbornik Statei*, Vol. 42, 1973, pp. 59-65, 2 refs., In Russian.
Icebreaking, icebreakers, ice adhesion, young ice.
28-2605

**Remote sensor for measuring the speed of ship models in ice**, Lipatov, V.N. and Lobox, V.I., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, *Ice Navigation Qualities of Ships*, Edited by D.E. Kheisin and IU.N. Popov, pp. 245-251, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 2 refs.
Ice navigation, ships models, ice models, motion studies.
28-1565

**Icebreakers**, Faddyeer, O.V., Iagodkin, V.IA., Kashtelian, V.I., and Ryvlin, A.IA., Engineering Laboratory, Aug. 1973, 263 pp., NTIS #AD-766 591, Translation of **Ledokoly**, Leningrad, Izdatel'stvo Sudostroenie, 1972, 77 refs. Icebreakers, ships. The book **Icebreakers** generalizes the experience that has been accumulated in the development and design of icebreakers, discusses methods of calculating their ice performance, design, and arrangement features, and points out paths toward further improvement. All present Soviet and foreign icebreakers are described, their operating conditions are analyzed, the basic ice performance characteristics of an icebreaker are examined (ice speed to power ratio, ice strength, maneuverability, jamming conditions), and methods of evaluating these qualities, developed by Soviet specialists, are set forth; the design features of the basic machinery and systems of icebreakers are noted; recommendations on their design are presented. A considerable part of the book is devoted to features of the choice of hull shape, main dimensions, and power plant. Data on icebreakers, hull design, and relations for determining the strength dimensions of the framing and plating are presented. The power plants are analyzed and diagrams of the electric power plants of icebreakers presently in operation are presented; requirements imposed on these diagrams are formulated. Features of the design and calculation of special icebreaker systems (list and trim systems) are discussed. Materials on certain general ship systems (towing, steering, and helicopter systems) are presented. Features of an icebreaker's control systems are described and the prospects and trend of its development are discussed.
28-3033

**Ice-clearing cutter**, Eqorov, V.V., Makeenko, V.I., and Mal'tsev, V.S., *Soviet Inventions Illustrated*, Section 3, *Mechanical and General*, 1974, p. 01.
Ice cutting, icebreakers.
28-3138

**Ship's hydraulic ice-cutter**, Arshevevskii, IU.A., Grebennikov, L.P., and Tsykin, E.M., *Soviet Inventions Illustrated*, , Section 3, *Mechanical and General*, 1974, p. T2. Ice cutting, icebreakers, ship icing.
28-3201

**Hull lubrication for icebreaking on the WYTM RARITAN**, U.S. Coast Guard Office of Research and Development, Report No. 731342 95, Feb. 1973, NTIS #AD-757 937.
Ships, marine engineering, icebreakers, lubricants, water films, ice water interface, bubbling, measuring instruments, ice cover thickness, ice strength.
28-3284

**Measurement of resistance, ice loads, and ice characteristics on the USCGC MACKINAW**, Edwards, R.Y., Jr., Leving, G., Lewis, J.W., and Wheaton, J.W., U.S. Coast Guard Office of Research and Development, Report No. 731343, Feb. 1973, 61 pp. + 30 pp. appends., NTIS #AD-759 952, 11 refs.
Ships, marine engineering, icebreakers, lake ice, ice cover, thickness, ice strength, dynamic loads, measuring instruments.
28-3285

**Experimental determination of ice impact loads on marine vehicles**, Edwards, R.Y. and Wheaton, H.W., *Symposium on Ice and Its Action on Hydraulic Structures, 2nd*, Leningrad, 26-29 September 1972, Papers, pp. 51-61, With French summary.
Icebreakers, impact tests, strain analysis, lake ice.
28-3857

**Experimental determination of ice impact loads on marine vehicles**, Edwards, R.Y. and Wheaton, H.W., *Symposium on Ice and Its Action on Hydraulic Structures, 2nd*, Leningrad, 26-29 September 1972, Papers, pp. 51-61, With French summary.
Icebreakers, impact tests, strain analysis, lake ice.
28-3857

**Modelling the motion of ships through polar ice fields using unconstrained, self-propelled models**, Edwards, R.Y., Jr., and Lewis, J.W., *Symposium on Ice and its Action on Hydraulic Structures*, Reykjavik, Iceland, 7-10 Sept. 1970, Papers and discussions, Reykjavik, Iceland, International Association for Hydraulic Research, 1970, 18 pp., 5 refs.
Includes discussions. Models, Ships, Ice navigation, Icebreakers, Ice cover thickness, Arctic regions.
28-4007

**Speed of ship movement in broken ice**, Sandokov, I.O., *Fechnci Transport*, No. 2, 1974, p. 51, In Russian.
Ice navigation, Ships, River ice, Velocity, Experiments.
29-139

**Ice-breaker ship bow end**, IAkovlev, M.S. and Zefirov, A.S., *Soviet Inventions Illustrated*, Section 3, *Mechanical and General*, Vol. 18, 1974, p. 12.
Icebreakers.
29-474

**Jet compressors for navigating ship in ice**, Evdokimov, S.I., Kashtelian, V.I., and Kovalenko, V.K., *Soviet Inventions Illustrated*, Section 3, *Mechanical and General*, Vol. 15, 1974, p. 14.
Ice navigation, Ice removal equipment, Bubbling.
29-483

**On the role of bow friction in icebreaking**, Scarton, H.A., *Journal of Ship Research*, Vol. 19, No. 1, March 1975, pp. 34-39, 13 refs.
Ice breaking, metal ice friction, ice breakers, dynamic loads, mathematical models.
29-3795

**Icebreaking modeling**, Atkins, A.G., *Journal of Ship Research*, Vol. 19, No. 1, March 1975, pp. 40-43, 5 refs.
Icebreaking, ice cover strength, mathematical models.
29-3796

**Proceedings, The Second International Conference On Port And Ocean Engineering Under Arctic Conditions**, *International Conference on Port and Ocean Engineering under Arctic Conditions, 2nd*, Reykjavik, Iceland, 27-30 Aug.1973, Reykjavik, University of Iceland, 1974, 801 pp., refs. Discussions follow several papers. For selected papers see 29-3877 through 29-3903.
Ports, ice navigation, ocean waves, offshore structures, icebreaking, sea ice, ice surveys, hydraulics, meeting, marine transportation.
29-3876

**Comparative model tests of the icebreaker performance of two Canadian Coast Guard icebreakers**, Edwards, R.Y., German, J.G., and Lawrence, R.G.A., *International Conference on Port and Ocean Engineering under Arctic Conditions*, Proceedings, pp. 80-100, 2 refs.
Icebreakers, ice resistivity, ice cover thickness, ice navigation, models, tests.
29-3880

**Determining specific failure energy and contact pressures at the impact of a solid body of ice**, Kheisin, D.E., Kurdiumov, V.A., and Likhomanov, V.A., Leningrad, Arkticheskii i antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 326, 1975, pp. 210-218, 6 refs., In Russian.
Ice navigation, icebreakers, ice breaking, impact strength, sea ice, ice strength, measuring instruments analysis (mathematics).
30-3634

**Ship model testing in ice, possibilities reliability**, Makinen, E., *International Conference on Port and Ocean Engineering under Arctic Conditions*, Proceedings, pp. 115-137, 9 refs.
Ships, ice navigation, icebreakers, ice breaking, ice conditions, models, tests.
29-3882

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Ground effect machines, ice bearing capacity, ice breaking, ice sheets, models, ice models, ice thickness, ice elasticity, ice strength.
30-1849

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Icebreakers, ice navigation, ice breaking, ice resistivity,

models, design criteria, sea ice, analysis (mathematics).
30-1835

**Variation of ship/ice parameters on ship resistance to continuous motion in ice**, Milano, V.R., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975, pp. B1/1-B1/26, 9 refs.
Icebreakers, ice breaking, design criteria, ice pressure, navigation, ice cover thickness, impact strength.
30-1837

**Ship resistance to continuous motion in mush ice**, Milano, V.R., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975, pp. B2/1-B2/32, 8 refs.
Icebreakers, ice navigation, ice pressure, velocity, analysis (mathematics), computer programs.
30-1838

**Model to predict hull-ice impact loads in the St. Lawrence**, Berenger, D.M., Lawrie, C.J.R., and Major, R.A., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975, pp. D1-D23, 23 refs.
Tanker ships, ice navigation, ice loads, impact strength, mathematical models, channels (waterways), computer applications.
30-1840

**Monopod drilling system for the Canadian Beaufort Sea**, Davies, J.F. and Jarawi, W., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975, pp. E1-E23, 12 refs.
Offshore drilling, drills, ice loads, sea ice, models, Beaufort Sea.
30-1841

**Ice resistance of a cargo vessel in the continuous mode of icebreaking: Tests of three geosim models in ice**, Koppenburg, M., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975, pp. L1-L12, 5 refs.
Icebreakers, ice pressure, ice cover strength, ships, tests, models, computer applications.
30-1848

**Influence of friction on ice resistance: Search for low friction surfaces**, Lahti, A., Makinen, E., and Rimppi, M., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975, 10 pp., 4 refs.
Icebreakers, ice pressure, protective coatings, metal ice friction, ice breaking, friction, tests.
30-1843

**Full scale testing in ice of three icebreakers**, German, J.G. and Lawrence, R.G.A., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975,pp. H1-H37, 5 refs.
Ice breakers, ice navigation, ice pressure, tests, models, velocity, penetration tests.
30-1844

**Scaling system for vessels modeled in ice**, Vance, G.P., *Ice Tech Symposium*, Montreal, Canada, 9-11 April 1975, Proceedings, New York, Society of Naval Architects and Marine Engineers, 1975, pp. H1/1-H1/28, 63 refs.
Icebreakers, ice navigation, ice pressure, mathematical models, ice cover thickness, tests, metal ice friction, resistance.
30-1845

**Modeling system for vessels in ice**, Vance, G.P., Kingston, University of Rhode Island, 1974, 366 pp., Ph.D. thesis, For abstract see Dissertation Abstracts International, Sec. B, Aug. 1975, p. 860.
Icebreakers, icebreaking, ice models, sea ice, analysis (mathematics).
30-1502

**Ship resistance in homogeneous ice fields: theory, systematic tests, and estimation of resistance and effective power at constant speed**, Chu, F.D., Ontanieni, Helsinki University of Technology, 1974.

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## II. Strength — Properties

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Ice mechanics, sea ice, elastic properties.
23-4224

**Model study of ice pressures**, Nuttall, J. et al, National Research Council, Canada, Associate Committee on Geotechnical Research, Technical Memorandum No. 92, March 1968, pp. 125-130, *Ice Pressures Against Structures*, Proceedings of a conference held at Laval University, Quebec, 10-11 November 1966, 3 refs.
Ice push, ice strength, models.
23-4230

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Geophysical institute strain tests, sea ice, ice mechanics, compressive strength.
23-5292

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Static loads, dynamic loads, ice pressure, structures, icebreakers, ice breaking. This monograph summarizes existing knowledge on forces exerted by an expanding ice sheet, impact forces of ice on structures, and vertical forces exerted by ice on hydraulic structures. Sections are also devoted to icebreakers and ice models.
25-1650

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Ice pressure, offshore structures, ice mechanics, dynamic loads, static loads.
26-1615

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Ice cover strength, ice hardness, ice sampling, tests, laboratory techniques.
26-1966

**Mechanical properties of sea ice with reference to structural behavior of ice sheets**, Pister, K.S., U.S. Naval Civil Engineering Laboratory, Hueneme, Calif., Technical Note, Sept., 116 pp., NTIS #AD-621 042.
Sea ice, ice mechanics, analysis (mathematics), ice sheets. A reasonable starting point for developing constitutive equations for the mechanical behavior of sea ice would be the fundamental theories advanced in the research of metals at elevated temperatures. In some areas, the advanced theory appears to be adaptable to the study of mechanical behavior of sea ice, while in others, constitutive equations will have been developed.
26-2240

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Ice cover strength, ice navigation, ice reporting, ice forecasting, ice cover thickness, snow cover effect, river ice, sea ice.
27-2056

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Ice cover strength, test chambers, test equipment, icebreakers, ice navigation, models, laboratory techniques.
27-2057

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Ice breakup, ice friction, ice physics, ice deformation, ice strength, ice models, river ice, mathematical models.
28-3579

Sea ice, ice growth, drive, ice navigation, ice reporting, ice forecasting, classifications.
29-7

**Scale models for investigation of ice phenomena**, Starosolszky, O., *Symposium on Ice and its Action on Hydraulic Structures*, Reykjavik, Iceland, 7-10 Sept. 1970, Papers and discussions, Reykjavik, Iceland, International Association for Hydraulic Research, 1970, 3 pp., 3 refs., In English with French summary.
Ice models, hydrodynamics, ice cover effect.
28-4005

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Ice models, floating ice, hydrodynamics, hydraulic structures.
28-4006

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Ice models, hydrodynamics, floating ice, water transport.
28-4008

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Ice strength, strain rate, compressive strength, tensile strength, stress strain diagrams, stress analysis, snow ice.
28-550

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Ships, ice loads, ice navigation, impact strength, analysis (mathematics).
28-1558

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Ice breaking, ice physics.
29-2512

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Low temperature research, artificial ice, laboratory techniques, ice models, ice breaking, sea ice, research facilities.
29-3344

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Floating ice, ice mechanics, ice loads, ice physics, offshore drilling, stress-strain diagrams, sea ice.
30-1847

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## III. Navigation in Ice

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23-1735

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Sea ice, ice navigation.

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Navigation, sea ice, ice breaking, artificial melting.
23-2530

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Ships, ice navigation.
23-3238

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Ice navigation, icebreakers.
23-4903

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Expeditions, icebreakers.
23-4942

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Icebreakers.
23-5534

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Ice navigation, spaceborne photography, sea ice, Antarctica.
23-5803

**Navigational oceanography**, Dromliug, V.V., Filippov, IU.M., and Ukhanov, G.I., Moscow, *Transport*, 1965, 291 pp. (Pertinent pages: 54-64, 103-108, 195-204, 238-244), 20 refs., In Russian.
Sea ice, ice navigation, icebreakers. Selected pages cover the following topics: general information on ice cover in seas; its formation, growth, deterioration; ice classification; physical and mechanical properties of sea ice; radar techniques of ice observation from ships; ice-navigation manuals and atlases; mathematical procedures associated with ice navigation.
24-115

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Sweden, icebreakers, sea ice.
24-188

**Determining passibility of river ice for vessels**, Iakovlev, M.S., Gor'kii, Politekhnicheskii institut, *Trudy*, Vol. 17, No. 1, 1961, pp. 5-23, 6 refs., In Russian with English table of contents enclosed.
River ice, ice navigation, ships.
24-416

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Ships, ice breaking, ice navigation, ice breakers, cold weather operation.
24-1189

**Navigation and technical operation of a vessel**, Anosov, A.V., and Didyk, A.D., Moscow, *Transport*, 1969, 483 pp. (pertinent pages 378-398), In Russian.
Sea ice, ice navigation, icebreakers, ice breaking.
24-1796

**Icebreaker support for winter navigation**, Pohjanpalo, J., *Navigator*, No. 3, 1969, pp. 16-19, In Finnish.
Icebreakers, ice navigation.
24-211

**Maintenance and repair of fishing vessels**, Kushnarev, V.A., Moscow, *Pishchepromizdat*, 1951, 179 pp., 9 refs., In Russian.
Ice navigation.
24-2127

**Using river icebreakers in lower courses of major Siberian rivers**, Antonov, V.S. and Pozniak, I.I., Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'ski institut, *Trudy*, Vol. 283, 1968, pp. 157-164, In Russian.
River ice, ice breaking, icebreakers.
24-2349

**Survey report on Great Lakes and St. Lawrence Seaway - navigation season extension**, U.S. Corps of Engineers, Detroit District, Detroit, Michigan, 1969, various pagings, Includes Donald R. Rondy, *Great Lakes Ice Atlas*, For which see 24-1312. Bibliography pp. B-1 thru B-9.
Lake ice, river ice, ice navigation, icebreakers, ice control.
24-2662

**Ice navigation with icebreakers**, Pushkarev, L., Sandakov, IU., and Tronin, V., *Rechnoi Transport*, 1969, pp. 37-38, In Russian.
Icebreakers, ice navigation.
24-2840

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Arctic Ocean, ice navigation, icebreakers.
24-2976

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S.S. MANHATTEN, tanker ships, northwest passage, icebreakers, ice breaking, ice navigation, sea ice.
25-580

**Future polar transport**, Whitelaw, A.H., *Sea Frontiers*, Vol. 16, No. 4, July/Aug. 1970, pp. 206-210.
Undersea vehicles, northwest passage, sea ice, transportation, vehicle, ice navigation.
25-694

**Strength of ships sailing in ice**, Faddyeer, O.V., Kheisin, D.E., Iakovlev, A.A., and Popov, IU.N., U.S. Army Material Command, Foreign Science and Technology Center, Technical translation, Report No. FSTC-HT-23-96-68, 5 Feb. 1969, 228 pp., 58 refs., NTIS #AD-684 596.
Shipbuilding, icebreakers, ice navigation, sea ice, ice cover strength, design criteria.
25-1173

**Testing strength of ships under natural ice navigation conditions**, Igant'ev, M.A. and Tyvlin, A.IA., *Problemy Arktiki i Antarktiki, Sbornik statei*, Vol. 33, 1970, pp. 119-123, In Russian.
Sea ice, chips, ice navigation, icebreakers, ice push.
25-1239

**Sea ice and ice navigation**, Tsurikov, V.L., **Morskoi sbornik**, No. 10, Oct. 1970, pp. 84-90, In Russian.
Sea ice, drift, ice navigation.
25-3453

**Possibility of winter navigation through the Northwest Passage**, Shpaikher, A.O. and Soboleva, D.R., *Problemy Arktiki i Antarktiki, Sbornik statei*, Vol. 5, 1970, pp. 67-75, 9 refs., In Russian.
Icebreakers, ice navigation, S.S. MANHATTEN, Northwest Passage.
25-3513

**Winter navigation on Lake Melaren**, Treshnikov, IU., *Rechnoi Transport*, No. 12, 1970, p. 51, In Russian.
Sweden-Melaren Lake, ice navigation, icebreakers.
25-3720

**Voyage of the S.S. MANHATTEN**, Nevel, D.E. and Weeks, W.F., *Military Engineer*, Vol. 62, No. 406, 1970, pp. 80-82.
S.S. MANHATTEN, icebreakers, ice mechanics. A series of tests of the icebreaking capabilities of the MANHATTEN were carried out in a homogeneous area of ice selected by helicopter reconnaissance, during which continuous measurements of thrust and vessel velocity were made. At the completion of each test, ice thickness, temperature and salinities, as well as strength and Young's modulus, were measured along the test track to characterize the state of ice.
25-4147

**Basic considerations of icebreaker mechanics**, Brown, S.E., *Northern Engineer*, Vol. 2, No. 1, Spring 1970, pp. 10-11, 1 ref.
Icebreakers, ice navigation, ice cover strength.
25-4294

**Making navigation in the arctic more profitable**, Gordienko, P.A., *Problemy Arktiki i Antarktiki, Sbornik statei*, Vol. 36-37, 1970, pp. 135-141, 3 refs., In Russian.
Ice navigation, ice forecasting, sea ice distribution, aerial reconnaissance, icebreakers, navigation costs.
26-267

**Ice-breaking research and supply ship for British Antarctic Survey**, *Motor Ship*, Vol. 51, No. 608, March 1970, pp. 536-537.
Icebreakers, ships, design criteria.
26-451

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Icebreakers, ice breaking, river ice, ice removal equipment, heat transfer, cost analysis.
26-712

**Maneuvering in harbors, at sea**, Kluge, K. and Koch, W., Hamburg, 1966, 184 pp. (pertinent pp. 139-173), In German.
Ice navigation, icebreakers, sea ice, ice reporting, ice push, propellers.
26-940

**Scientific provisions for navigation in Eastern Arctic in 1970**, Kupetskii, V.N., *Geograficheskoi obshchestov SSSR*, Vol. 104, No. 4, July-Aug. 1971, pp. 239-352, 8 *refs., In Russian.*
Sea ice, drift, ice surveys, ice navigation, forecasting, ice reporting, icebreakers.
26-972

**Ice breaking boat used in timber floating**, Agalakov, R. and Metelev, S., *Lesnaia promyshlennost'*, No. 5, May 1971, p. 14, In Russian.
Icebound rivers, icebreakers, ships, diesel engines, ice breaking, ship icing, countermeasures.
26-1289

**Icebreaker channel improvement**, Ivanov, V.M., Pekhtusov, M.V., and Titov, I.A., *Soviet Inventions Illustrated*, Section 3, *Mechanical and General*, August 1971, p. 8E.
*Icebreakers, ships, propellers, sea ice, ice breaking.*
26-1909

**Calculating the passability of icebreakers through sea ice**, Vitko, N.A., Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 300, 1971, pp. 201-212, In Russian.
Icebreakers, ice navigation, ice cover thickness, ice cover strength, ice breaking, analysis (mathematics).
26-1982

**Icebreakers for cutting channels free of ice**, Shvaishten, Z.I., *Problemy Arktiki i Antarktiki, Sbornik statei*, Vol. 38, 1971, pp. 133-136, In Russian.
Icebreakers, ice cutting, ice navigation. The "ice-plows" described are special attachments for ice-breakers and other vessels, for cutting ice cover up to 2 m thick and through ice-block piles up to 7 m high.
26-2376

**Problems of operating large ships in the arctic**, Maybourn, R., *Institute of Navigation, Journal*, Vol. 24, No. 2, April 1971, pp. 135-146, Includes discussion.
Ice navigation, sea ice, ice condition, S.S. MANHATTEN, aerial reconnaissance, Arctic Ocean.
26-3518

**Ice-breaker for channel clearing**, Ignat'ev, M.A., *Soviet Inventions Illustrated*, Section 3, *Mechanical and General*, Nov. 1971, p. E3.
Icebreakers, river ice.
26-3727

**Ability of the R/V OB to operate in Antarctic Sea ice**, Romanov, A.A., Sovetskaia antarkticheskaia ekspeditisiia, 1955-, *Information Bulletin*, No. 5, April 1971, pp. 414-416, 5 refs., Translated from its *Informatsionny i biolleten'*, No. 75, 1969.
Ice navigation, icebergs, drift, icebreakers, ice cover distribution, snow cover distribution, snow depth. The results of ice observations during voyages in Antarctic seas from 1955 to 1966 were used to determine the speed of the OB, which belongs to the ice class of vessels of the reinforced Arctic ice type. Data are given on navigation of the OB during operations in water with icebergs, in drift ice during the freezing period. The technical or maximum safe speeds of the OB under various conditions can be used to determine navigation time and speed of advance of ships of her class in Antarctic ice.
27-136

**Efficiency of channel cutting in the fast ice of Mieny and optimum time for forcing it**, Romanov, A.A., Sovetskaia antarkticheskaia ekspeditsiaa, 1955-, *Information Bulletin*, Vol. 7, No. 5, April 1971, pp. 453-456, 14 refs., Translated from its *Informatsionnyi biolleten'*, No. 76, 1969.
Sea ice, fast ice, ice cutting, icebreakers, ice navigation, Antarctica-Mirnyy Station. To determine the technical or maximum safe speeds during the cutting of a channel in the fast ice, the logs of the OB and the results of observations during the forcing of the fast ice at Mirnyy, Molodezhnaya, and Lazarev Stations in

1956-1966 were studied. The channel cutting efficiency, being a function of the thickness of the fast ice and of the snow cover depth, increases most markedly for ice thickness of less than 150 cm. The time for the completion of unloading operations on the fast ice, investigated near Mirnyy station, depends on the structure, stratigraphy, formation, and disintegration of the fast ice. The optimum date to start forcing the fast ice is in the latter part of Oct. because the ice reaches total thickness. After investigating the fast ice just before a ship approaches, it is necessary to verify the channel forcing time against the cutting speed, proceeding with the analysis of the actual ice thickness distribution, snow depth, and fast ice width.
27-138

**Cutting of passages through floating ice fields**, Koblov, I.T., *Soviet Inventions Illustrated*, Section 3, *Mechanical and General*, Jan. 1972, p. E6.
Ice cutting, floating ice, ice navigation.
27-162

**Methods of extending the working period of ships**, Borodkin, B.S., *Trudy koordinatsionnykh soveshchanii po gidrotekhnike*, No. 17, 1965, pp. 164-173, 3 refs., In Russian. Polynyas, ships, hydraulic structures, deicing, ice breaking, ice melting.
25-1590.

**Trial calculation of icebreaker passability through sea ice**, Vitko, N.A., Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Transactions, Trudy*, Vol. 300, IAkovlev, G.N., *Ice physics and ice engineering*, Jerusalem, Israel Program for Scientific Translations, 1973, pp. 181-183, For Russian original see 25-1982.
Icebreakers, ice navigation, ice cover thickness, ice cover strength, ice breaking, analysis (mathematics).
27-2074

**Transportation conditions at the Kolyma River estuary**, Antonv, V.S., Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 297, 1972, pp. 69-74, 7 refs., In Russian.
Icebound rivers, ice navigation, icebreakers, ice cutting, USSR-Kolym River.
27-2386

**Ice navigation of river vessels**, Pushkarev, L.V. and Tronin, V.A., Moscow, Transport, 1973, 113 pp., 32 refs., In Russian with English table of contents enclosed.
Ice navigation, icebreakers, icebound rivers.
28-274

**Voyage of the U.S. tanker MANHATTEN through the Northwest Passage**, Minevich, A.IA., *Problems of the Arctic and the Antarctic*, Issues 33-35, edited by A.F. Treshnikov, Jerusalem, Israel Program for Scientific Translations, 1973, pp. 337-341, 7 refs., For Russian original *see* 25-3512.
Ice navigation, icebreakers, ice breaking, tanker ships, sea ice.
28-491

**Experiences from engineering works in the port of Drammen**, *International Conference on Port and Ocean Engineering Under Arctic Conditions, 1st*, Proceedings, Vol. 1, 1971, pp. 319-325.
Ports, ice breaking, snow removal, Norway-Drammen.
28-553

*Ice Navigation Qualities of Ships*, Kheisin, D.E. (ed.) and Popov, IU.N. (ed.), U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL 417, 281 pp., NTIS #AD-764 807, Translation of Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973., For individual papers see 28-1544 through 28-1568.
Icebreakers, propellers, ice navigation, sea ice, ice breaking, ships, ice loads, metal ice friction, wood ice friction, ice cover strength, ice hardness, models.
28-1543

**Methods of estimating the ice navigating capability of a ship in solid ice**, Kashtelian, V.I., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 3-18, NTIS #AD-764 807, Translation from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 12 refs.
Ice navigation, ships, ice loads, ice breaking, icebreakers.
28-1544

**On the ice navigation speed of ships in extremely solid ice**, Kheisin, D.E., U.S. Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 19-30, NTIS #AD-764-807, Translation from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 13 refs.

Ice cover strength, ice hardness, ice friction, ice cutting, ice breaking, mathematical models, ice navigation. The stability of the motion of a ship in solid ice with a thickness close to the limiting thickness is investigated. The probability of stopping for given intervals of time is estimated. An estimate is given of the dispersion of the force of the ice resistance according to a three-point static scheme of icebreaking. Dimensionless parameters are introduced that make it possible to compare the ice navigation speed (ice navigating capability) of ships of the same type. Calculated thicknesses of ice broken for various ships, including the LENA, are tabulated.
28-1545

**On the distribution of probabilities of the number of impacts of a ship's hull against the ice**, Kheisisn, D.E., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417,*Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 136-141, NTIS #AD-764 807, Translation from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 2 refs.
Ice navigation, ships, ice loads, impact strength, statistical analysis.
28-1555

**Elastic oscillations of a ship's hull in the effect of random pulsed ice loads**, Kheisin, D.E., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 153-159, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 4 refs.
Ships, ice navigation, ice loads, motion studies, analysis (mathematics).
28-1557

**Determination of the pliability factors of the elastic coverings of frames in the effect of an ice load**, Faddyeer, O.V. and Likhomanov, V.A., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 173-179, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 2 refs.
Ice navigation, ships, ice loads, design.
28-1559

**On the calculation of the side shell plating in the effect of an ice load**, Solostinaski, D.I., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 180-199, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 7 refs.
Ice navigation, ships, ice loads, design.
28-1560

**Marine transport with commerical ice vessels in arctic regions**, Kallipke, F., 1972, 15 pp., Trans. from*Schiff und Hafen*, No. 10, 1972.
Marine transportation, ice navigation, icebreakers, design, shipbuilding, marine propellers.
28-1920

**Observations data on the speed of ship movement in ice-covered sea**, Romanov, A.A., **Sovetskaia antarkticheskaia ekspeditsiia, 1955-**, *Trudy*, No. 59, 1973, pp. 86-94, In Russian.
Ice navigation, sea ice distribution, ice cover thickness, icebreakers. The speed of the ships OB and PROFESSOR VIZE were calculated in ice-covered waters. The speed of the PROFESSOR VIZE in the Davis Sea following the OB was 9.5 knots in ice of 1-3 marks, 6.5 knots in ice of 4-6 marks, 5 knots in ice of 7-9 marks. The OB attained 3.5 knots in another area in ice of 9-10 marks and 2.2 knots in ice of 10 marks at full power. The variety in ice conditions according to region is described.
28-2402

**New methods for allowing for the effect of ice cover on navigation**, Gordienko, P.A. and Smirnov, V.I., Issledovaniia l'dov iuzhnykhmorei SSR, Moskow, Nauka, 1973, pp. 64-68, 1 ref., In Russian.
Icebreakers, ice navigation, sea ice, ice breaking, ice cover thickness, drive, pressure ridges.
28-2831

**Use of probability methods in estimating the maneuvering qualities of ships in ice**, Kheisin, D.E., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 48-58, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 11 refs.
Icebreakers, ice navigation, ice cutting, ice friction, impact strength, ice floes, drift, mathematical models.
38-1547

**Investigation of the inertial characteristics of unsteady-state motion of an icebreaker in ice,**

Ryvlin, A.IA. and Tegkaeva, T.Kh., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 59-65, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 2 refs.
Icebreakers, ice navigation, motion studies, theories, analysis (mathematics).
28-1548

**Wedging of icebreakers in ice**, Kashtelian, V.I. and Popov, IU.N., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 66-81, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 8 refs.
Drift, ice navigation, icebreakers, ice breaking, motion studies, analysis (mathematics), sea ice.
28-1549

**Strength of icebreakers and transport vessels**, Likhomanov, V.A., U.S. Army Cold Regions Research and Engineering Laboratory, Aug. 1973, CRREL transl. #TL417, *Ice Navigation Qualities of Ships*, edited by Kheisin, D.E. and Popov, IU.N., pp. 115-127, NTIS #AD-764 807, Translated from Leningrad, Arkticheskii i Antarkticheskii nauchno-issledovatel'skii institut, *Trudy*, Vol. 309, 1973, 3 refs.
Icebreakers, ice cutting, ice loads, ships impact strength, analysis (mathematics).
28-1553

**Cold regions marine technology: current contributions and future challenges**, Edwards, R.Y., Jr., *Naval Engineers Journal*, Vol. 85, No. 4, Aug. 1973, pp. 35-52, 34 refs., Includes comments by P.B. Mentz and C.A. Richmond.
Marine transportation, ice conditions, icebreakers, ice navigation, channels (waterways), hydraulic structures, marine engineering.
18-1825

**Preliminary report of the observation of sea ice pressure and its effect on merchant vessels under icebreaker escort**, Bradford, J.D., *International Conference on Sea Ice*, Reykjavik, 10-13 May 1971, Proceedings, Reykjavik, Iceland, National Research Council, 1972, pp. 154-158, 8 refs., Includes discussion.
Ice pressure, pack ice, wind velocity, ships.
28-2483

**On problems of a North American arctic marine transportation system**, *International Conference on Sea Ice*, Reykjavik, 10-13 May 1971, Proceedings, Reykjavik, Iceland, National Research Council, 1972, pp. 239-240.
Marine transportation, ice navigation.
28-2492

**Dry cargo vessel for the waterways of Siberia and the Far East**, Boqdanov, B.V., *Sudostroenie*, No. 11, Nov. 1973, pp. 3-6, In Russian.
Ice navigation, ships, arctic regions, icebreakers.
28-1752

**Geophysical investigation in arctic seas**, Gorodnitskii, A.M. and Grinberg, V.M., *Zemlia i uselennaia*, No. 3, May-June 1973, pp. 58-60, In Russian.
Geophysical surveys, ships, ice navigation, icebreakers, arctic ocean.
28-1753

**Proceedings, Great Lakes-St. Lawrence Seaway Winter Navigation Seminar**, Detroit, Dec. 1972, 238 pp.
River ice, ice control, ice navigation, cost analysis, marine transportation, safety, meetings. This collection of addresses presented during the seminar deals basically with the impact of extending the St. Lawrence Waterway shipping season through the winter by various methods of controlling or dispersing river ice. A number of agencies, both government and private, express viewpoints on what has been done and needs to be done to control ice in the waterway; on insurance involved; on costs of extending the navigation season and benefits that would accrue thereby; on labor organizations' position on the extended season and the human problems that would result, particularly stressing safety factors; on the shipping industry's emphasis on winter navigation, cargo handling, and costs; on power authorities; cautions about upsetting the St. Lawrence flow balance; and on environmentalists' concern regarding the effect on nearby environments if the navigation season is extended.
28-3419

**Ice strengthening of Great Lakes ore carriers - a computer-aided analysis**, Kaldjian, M., Ann Arbor, University of Michigan, Dept. of Naval Architecture and Marine Engineering, 1973, 24 pp.
Marine transportation, ships, lake ice, ice navigation, computer applications.
28-3594

**Ways of increasing the profitability of arctic navigation**, Gordienko, P.A., *Problems of the Arctic and Antarctic*, Collection of articles, Vol. 36-37, edited by Treshnikov, A.F., New Delhi: Amerind Publishing Co., Pvt. Ltd., 1973, pp. 174-181, 3 refs., For Russian original see 26-267.
Ice navigation, ice forecasting, sea ice distribution, aerial reconnaissance, icebreakers.
28-3771

**Ice-breakers for making ice-free channels**, Shvaishtein, Z.I., *Problems of the Arctic and Antarctic*, Collection of articles, Vol. 38, edited by Treshnikov, A.F., New Delhi: Amerind Publishing Co. Pvt. Ltd., 1973, pp. 170-175, For Russian original see 26-2376.
The "ice-plows" described are special attachments for icebreakers and other vessels for cutting ice cover up to 2 m thick and through ice-blocks piled up to 7 m high. Icebreakers, ice cutting, ice navigation.
28-4059

**Experience of the Murmansk Hydro Meteorological Service in providing information for fishing and navigation in arctic seas and the north Atlantic Ocean**, Terziev, F.S., *Meteorologiia i gidrologiia*, No. 2, Feb. 1974, pp. 108-113, 10 refs., In Russian.
Ice navigation, weather forecasting, ice reporting, weather station, Arctic Ocean.

**Shipping lane ice breaking system**, Malkov, O.E., Maniukov, A.S., and Pyzihikov, A.V., *Soviet Inventions Illustrated*, Section 3, *Mechanical and General*, Vol. 13, 1974, pp. U6-7.
Icebreakers.
28-4237

**Scientific provision for navigation in the eastern Arctic in 1972**, Kupetskii, V.N., Geograficheskoe obshchestvo SSR., *Izvestiia*, Vol. 106, No. 1, Jan.-Feb. 1974, pp. 78-80, 2 refs., In Russian.
Ice navigation, ice reporting, ice forecasting, icebreakers, drift, meteorological factors, Arctic Ocean.
28-4314

**Sea-ice pressure generation and its effect on navigation in the Gulf of St. Lawrence area**, Bradford, J.D., Institute of Navigation, London, *Journal*, Vol. 24, No. 4, Oct. 1971, pp. 512-520, 12 refs.
Ice pressure, ice navigation, wind factors, sea ice, Canada--Gulf of Saint Lawrence.
29-91

**Ice breaking drilling ship for offshore exploratory drilling in the arctic**, Jones, K.M. and Schaff, J.C., *Offshore Technology Conference*, Preprints, Vol. II, Houston, Tex 1973, pp II-333 - II-350, 13 refs.
Ships, icebreakers, offshore drilling.
29-582

**Method of clearing a path through ice**, Bastian, C.E., Jr., U.S. Patent Office, 7 May 1974, 8 pp.
Icebreakers.

**Transportation in the Arctic**, Paddison, F.C. and Stone, A.M., *Polar Deserts Symposium*, Philadelphia, 1971, edited by Smiley, T.L., and Zumberge, J.H., Tucson, University of Arizona Press, 1974, pp. 125-149, 29 refs.
Transportation, ground effect machines, airplanes, icebreakers, fuel transport, trafficability, permafrost, logistics.
28-873

**Ice conditions for navigation in waters of the Canadian-Alaskan arctic**, Smirnov, V.I., Leningrad, *Gidrometeorizdat*, 1974, 179 pp., 140 refs., In Russian.
Ice navigation, sea ice, river ice.
29-969

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River ice, ice breaking, ice navigation, flood control, Netherlands.
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Sea ice, lake ice, river ice, ice breaking, ice control, ice navigation.
29-2284

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Tanker ships, ice navigation, ships, icebreakers, ice-

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